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Upgrading Army Water and Wastewater
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Development of the Pipe Loop System for Determining Effectiveness of Corrosion Control Chemicals in Potable Water Systems

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In the Army's 12,000 miles of water lines, internal corrosion slowly destroys a large investment and creates significant problems for Army water treatment plant operators, who try to maintain the water quality at acceptable levels. Corrosion can be slowed using corrosion-inhibiting chemicals, but it is difficult to measure the extent of corrosion and the effectiveness of inhibitors without excavating actual pipes.

This study surveyed corrosion-inhibiting water quality control chemicals and methods for monitoring corrosion. With this knowledge, a pipe loop system was developed and installed at Fort Bragg, NC and Fort Monroe, VA. It was shown to be effective in gathering data on corrosion rates. After a standard procedure has been established, this loop will allow a water treatment plant operator to monitor with ease the effectiveness of corrosion-inhibiting treatments.

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FOREWORD

This work was done for the Facilities Engineering Division (now part of the U.S. Army Engineering and Housing Support Center), Office of the Assistant Chief of Engineers (OACE) under Project No. 4A62720A896, "Environmental Quality Technology"; Technical Area B, "Environmental Design and Construction"; Work Unit 048, "Upgrading Army Water and Wastewater Treatment Plants." The Technical Monitor was T. Wash, CEHSC-FU-S.

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EVALUATING EFFECTS OF WATER QUALITY CONTROL CHEMICALS IN WATER DISTRIBUTION SYSTEMS

1 INTRODUCTION

Background

Ordinary drinking water can extensively damage water treatment plants by corroding their metal components. Some of the effects of metal deterioration due to the corrosive action of potable water are leakage, reduced carrying capacity, structural failure associated with main breakage and street washout, and deteriorating water quality as corrosion products enter the potable water system (e.g., "red water"). Nationwide, drastic economic losses have been reported due to internal corrosion of water distribution system materials. In 1979, the National Bureau of Standards (NBS) reported that annual corrosion costs in the water supply field totaled about \$700 million.¹ Actually, far greater costs are incurred through damage to interior piping and plumbing systems in homes.² The Army also faces large costs due to corrosion in the drinking water treatment plants it owns, operates, and maintains. These systems, which include 12,000 miles of pipe at permanent installations, represent a major investment for the Army, so cost effective corrosion control is important.

Aside from economic concerns, regulatory issues must be considered. Corrosion products that enter the water distribution system lead to violations of the Safe Drinking Water Act, which requires that water quality regulations be met at the consumer's tap. The U.S. Environmental Protection Agency (USEPA) recognizes that corrosion problems are unique to each water supply system and thus sets forth regulations (National Interim Primary Drinking Water Regulations [NIPDWR])³ to identify potentially corrosive waters and to determine what materials are present in distribution systems.

For both maintenance and regulatory purposes, it is necessary to carefully evaluate and monitor the physical condition of the materials in the distribution system. There has been no simple, standard procedure for doing this. The actual materials cannot be examined unless they are excavated. It would be very difficult to define general rules for the effect of a particular water on a particular material because water qualities and distribution system materials vary worldwide, creating a huge matrix of parameters. Many of these parameters are difficult and expensive to measure. Methods do exist, but the regulations do not specify any standard procedures. Each plant tests differently and reports the results differently, so it is extremely difficult to make meaningful comparisons of water characteristics from place to place.

¹L. H. Bennett, et al., "Economic Effects of Metallic Corrosion in the United States," *Corrosion '79* (National Association of Corrosion Engineers [NACE], Atlanta, GA, March 1979).

²R. A. Ryder, "The Costs of Internal Corrosion in Water Systems," *Journal of the American Water Works Association*, Vol 72, No. 5 (1980), p 267.

³USEPA, "National Interim Primary Drinking Water Regulations," *Code of Federal Regulations*, Title 40, Part 141 (1981), pp 309-354.

This lack of standard methodology impairs the evaluation of the various corrosion-inhibiting chemicals. These chemicals can reduce a water's corrosive effects, but their effectiveness depends largely on characteristics of the water in which they are used. There is a bewildering array of treatment options, but water treatment plant operators presently have no systematic means of determining which plan is best for their plants.

Thus, a need exists for a standard, simple, easily implemented apparatus and procedure that will allow a water plant operator to monitor the effect of various treatments, helping him or her evaluate the effectiveness of water quality control chemicals. If this helps the operator choose the most appropriate treatment for corrosion control, future maintenance costs may be reduced.

Objectives

The objectives of this study were:

1. To develop, primarily for the water treatment plant operator, a standard apparatus and procedure for selecting and determining the effectiveness of corrosion control chemicals in drinking water systems, which would enable the operator to maintain water quality.
2. To test this apparatus in the field.

Approach

Various corrosion control strategies were reviewed, along with their effects on distribution system materials. Also, methods for analyzing and evaluating the internal corrosion potential of water systems were compiled from the literature. These methods include evaluation of the characteristics of water supply, laboratory analysis, and field investigation techniques. Based on the information gathered, a standard apparatus to evaluate and monitor internal corrosion was designed, developed, and fabricated. This pipe loop system was installed at the water plants at Fort Monroe, VA and Fort Bragg, NC and operated under field conditions. The data obtained were interpreted to determine the existence and extent of corrosion, the possible influencing factors, and the effectiveness of alternative water treatment chemicals.

Scope

This report discusses chemicals and techniques in general terms only; details of procedures and equipment can be found in the references. Some preliminary data from both installations are discussed, but the purpose of this analysis is not to provide a final evaluation of the chemicals tested. Rather, it illustrates the type of data which can be obtained from the pipe loop systems. More comprehensive analyses will be performed in the future in the effort to establish a standard evaluation procedure.

Mode of Technology Transfer

It is recommended that the pipe loop system technology described in this report be universally adopted at all permanent Army installations as a standard apparatus for monitoring internal corrosion in water distribution systems. In the interim, all treatment

plant offices will be informed of this development through an Engineer Technical Note (ETN) and an Engineer Technical Letter (ETL). The U.S. Army Engineering and Housing Support Center (USAEHSC) will be the primary technology transfer agency: they will include the pipe loop system in their operator assistance program. The information in this report should be used to update Technical Manual (TM) 5-813-3, *Water Supply, Water Treatment*.

2 CORROSION CHARACTERISTICS OF WATER AND DISTRIBUTION SYSTEM MATERIALS

Corrosion may be defined as the deterioration of a material or its properties due to reaction with its surroundings. In the waterworks industry, the "material" which deteriorates may be a metal pipe or its fixtures, the cement in a pipe lining, or an asbestos-cement (A-C) pipe. For internal corrosion, the material reacts with water.⁴

Almost all waters can be corrosive to some degree. The corrosive tendency of a water depends on its physical, chemical, and biological properties and on the nature of the material with which the water comes in contact. For example, water which may be corrosive to galvanized pipe may be relatively noncorrosive to copper pipe in the same system.

Water Quality

In most cases, the corrosion phenomenon involves a complex interaction of several factors. The following presents the common water properties that are known to have an influence on the corrosion of a material.

Flow velocity and temperature are the two main physical characteristics of water that affect corrosion. Very high velocity water can cause physical erosion of the pipe material, but usually the velocity has a greater influence on the corrosion mechanisms which depend on the pH, dissolved oxygen, galvanic couplings, etc. Extremely low flows or stagnant waters have been shown to promote tuberculation and pitting in water mains.

An increase in water temperature, in general, increases the corrosivity. Water which shows no corrosive tendency in the distribution system may cause severe damage in hot water heaters and plumbing systems. However, in waters with high hardness, an increase in temperature increases the potential for calcium carbonate scale to form, which protects the metal from corrosion. On the other hand, excessive scale formation may lead to clogged pipes and heat exchangers.

The chemical water quality plays an important role in the corrosion reactions with metal. Table 1 presents the major chemical characteristics of water and their general effects on corrosion. Several of these factors are closely related and an understanding of their relationship will aid in understanding corrosion.

Dissolved oxygen in water has long been recognized as one of the most potent corrosive agents to ferrous metals. Oxygen accepts the electron given up by the corroding metal and allows the corrosion reaction to continue. The reaction products then enter the water system and create a "red water" problem.

The pH is a measure of the hydrogen ion, H^+ , concentration in water. Hydrogen ions also accept the electrons given up by a metal, allowing the corrosion to continue. The pH affects the formation or solubility of protective films. At pH values below 5 the corrosion of metals such as iron and copper occurs rapidly.

⁴J. E. Singley, et al., *Corrosion Prevention and Control in Water Treatment and Supply Systems*, Pollution Technology Review No. 122 (Noyes Publications, Park Ridge, NJ, 1985).

Table 1
Chemical Factors Influencing Corrosivity of Water*

Factor	Effect
pH	Low pH may increase corrosion rate; high pH may protect pipes and decrease corrosion rates
Alkalinity	May help form protective CaCO_3 coating, helps control pH changes, reduces corrosion
DO	Increases rate of many corrosion reactions
Chlorine residual	Increases metallic corrosion
TDS	High TDS increases conductivity and corrosion rate
Hardness (Ca and Mg)	Ca may precipitate as CaCO_3 and thus provide protection and reduce corrosion rates
Chloride, sulfate	High levels increase corrosion of iron, copper, and galvanized steel
Hydrogen sulfide	Increases corrosion rates
Silicate, phosphates	May form protective films
Natural color, organic matter	May decrease corrosion
Iron, zinc, or manganese	May react with compounds on interior of A-C pipe to form protective coating

*Source: J. E. Singley, et al., *Corrosion Prevention and Control in Water Treatment and Supply Systems*, Pollution Technology Review No. 122 (Noyes Publications, Park Ridge, NJ, 1985), p 15. Information originally obtained from Environmental Science and Engineering, Inc. Used with permission.

The alkalinity of water is its ability to neutralize acids. Alkalinity depends mostly on the concentrations of carbonates and bicarbonates, which in turn depend on pH. Carbonates and bicarbonates influence the water's ability to lay down a protective metallic carbonate coating. Alkalinity also controls the concentration of calcium ions that may be present in water at a specific pH.

Hardness, predominantly caused by the presence of calcium and magnesium, can help form a protective calcium carbonate lining on the pipe walls, under proper conditions.

Chlorides and sulfates, if present in high concentrations, have been shown to cause pitting of metallic pipes. The reaction products of chlorides and sulfates prevent the formation of protective metallic oxide films. The ratio of chloride plus sulfate to bicarbonate ($\text{Cl}^- + \text{SO}_4^{2-} / \text{HCO}_3^-$) has been used as an indicator of the corrosivity of water.

Many other substances in water, including hydrogen sulfide, natural color, organic matter, and microbial factors can influence corrosion reactions. A detailed discussion of these factors is beyond the scope of this report, but can be found in the literature listed in the reference section.

Water Distribution System Materials

The chemical properties of materials present in a water distribution system greatly dictate the extent of corrosion-related problems. The corrosion behavior of each material also is the basis for considering specific corrosion control alternatives.

A variety of materials are used by the water works industry for the construction of treatment plant, storage, distribution pipes, and internal plumbing. The majority of the materials are used in construction of pipes and storage.

Detailed information regarding the nature and magnitude of corrosion and corrosion control in the water works industry is presented by Singley et al. The following tables were selected from that document. Table 2 presents the common materials and their specific uses. Identifying what construction materials were used in a water utility requires researching records, archives, and surveys. Samples of old pipes which are being replaced also provide an opportunity to identify the type of material used. The significance of corrosion of various materials is presented in Table 3. This table presents a discussion of the known extent of use of each material as well as the contaminants that have been found associated with the use of each material. Table 4 presents an overview of the factors influencing or affecting corrosion of each material. Water quality parameters included are pH, hardness, alkalinity, dissolved oxygen, carbon dioxide, total dissolved solids, metal ion, and organic acids. The effect of velocity and temperature are also discussed.

Table 2
Types of Materials Used in the Water Industry*

MATERIAL	IN PLANT SYSTEMS:		TRANSMISSION LINES	STORAGE	DISTRIBUTION MAINS	SERVICE LINES	HOUSEHOLD
	PIPING	APPURTENANCES					
WROUGHT IRON	/				/	/	/
CAST/DUCTILE	//	//	//		/// (cast iron)	/	/
STEEL	/		/	//	/	/	/
GALVANIZED IRON	/				/	/	/
STAINLESS STEEL		//					/
COPPER	/	(brass)				///	//
LEAD		/	/		/	/	/
		(gaskets)					
ALUMINUM		/					/
ASBESTOS-CEMENT	/		//		//	/	
CONCRETE	/	/	//	//	/		
PLASTIC	/			/	/	//	//

KEY: /// Used >50% for the particular service.
 // Frequently used for the particular service.
 / Has been or is used for the particular service.

*Source: J. E. Singley, et al., *Corrosion Prevention and Control in Water Treatment and Supply Systems*, Pollution Technology Review No. 122 (Noyes Publications, Park Ridge, NJ, 1985), p 299. Used with permission.

Table 3
Effect of Corrosion of Materials Used
in the Water Industry*

MATERIAL	EXTENT OF USE	ASSOCIATED COMMENTS
IRON-BASED MATERIALS:		
PLAIN IRON	Cast iron is used in 75% of all major U.S. water supply distribution systems (17). [†] Also used in water appurtenances and treatment plants. Over 1/2 million steel water storage tanks exist in the U.S.	Iron concentrations in excess of the 0.3 mg/l approval limit occur, resulting in ferric oxide (red water) complaints.
GALVANIZED IRON	Generally limited to service lines, in-plant systems, and households. It requires threaded joints and gooseneck connections and is declining in usage.	Zinc concentrations will increase 5 to 10 mg/l after 8 to 40 hour exposure to new galvanized pipe. Small amounts of iron will enter solution. Cadmium and lead (impurities in galvanizing process) concentrations will rise.
STAINLESS STEEL	Seldom used for piping, but used where low maintenance and reliable, continuous service is desired, such as pumps, valves, meters, venturis, and pressure regulators.	Besides iron, other metals used to manufacture stainless steel that may enter the water through pitting or corrosion are chromium, nickel, and molybdenum.
COPPER	Extensively used in household piping and service lines. From World War II to 1972, over 6 million miles of copper tubing were put into service. Bronze may be used for appurtenances.	Copper, as well as iron, zinc, tin, and lead from associated pipes and solder may be oxidized into solution. Cu concentrations do not rise above about 5 mg/l. Impurities in brasses, such as manganese, arsenic, antimony, phosphorus, bismuth, and tin may also leak out.
LEAD	Little documentation available; according to Donaldson in 1924 (9) approximately 50% of water distribution systems in the U.S. had lead lines, used primarily for service lines and solders for copper pipes; ~60% of residences in Boston are serviced with lead lines.	Lead concentrations ranging up to ~0.3 PPM from both lead lines and lead-based solders have been reported.
ALUMINUM	Use of aluminum is relatively limited; currently used for weir gates, storage tanks, reservoir roofs and supports, hot water systems, and pipe lines.	No information available which identifies or quantifies potential contaminants; could release traces of copper, magnesium, silicon, iron, manganese, chromium, zinc, or titanium as well as alumina foms.
ASBESTOS-CEMENT	Approximately 1/3 of all water distribution pipe currently being sold in the U.S. is manufactured of asbestos-cement pipe; approximately 200,000 miles have been placed into service.	Asbestos-cement fibers counts in excess of 4.5 million fibers per liter have been observed; tetrachlorethylene concentrations as high as 2500 mg/l (3) have been observed from lined asbestos-cement pipes (22).
CONCRETE PIPE	Extensively used in water distribution (and storage) systems with service life of over 50 years in some locations. About 15% of new water tanks are concrete.	Contaminant release is greatest when the pipe is first used and decreases thereafter. Water hardness and pH initially increase. Oxides of silicon, aluminum, iron, magnesium, and sulfur may hydrolyze, releasing these elements.
PLASTIC PIPE	Currently growing in use for service lines and household piping except in hot water systems; 1978 use was about 1/3 of all piping on a footage basis. Recent development has produced larger pipes being used in distribution mains.	Lead stabilizing compounds may be leached from PVC pipes. Other contaminants arise from the solvents used and include 2-butanone (MEK) and tetrahydrofuran (THF).

*Source: J. E. Singley, et al., *Corrosion Prevention and Control in Water Treatment and Supply Systems*, Pollution Technology Review No. 122 (Noyes Publications, Park Ridge, NJ, 1985), p. 300. Used with permission.

**See table references on pp 54-56.

Table 4

Water Quality Characteristics That Minimize Corrosion of Materials Used in the Water Industry*

MATERIAL	pH	HARDNESS	ALKALINITY
IRON-BASED MATERIALS:			
PLAIN IRON	Long term: Little effect for pH 4-10 except localized corrosion may peak at pH 6-9 range (9). as Short term: pH effects are a function of flow rate and time (10).	Calcium (Ca^{++}) inhibits corrosion in the presence of sufficient alkalinity.	1. Greater alkalinity produces less aggressive water (34). 2. Anodic dissolution of iron is accelerated by bicarbonate HCO_3^- through the localized formation of $\text{Fe}(\text{CO}_3)_2$ (7).
GALVANIZED IRON	1. Corrosion rate increases inversely with pH. 2. Optimum pH range is 7-12.	Hard waters are less aggressive than soft waters (21, 37).	Greater alkalinity produces less corrosive waters.
STAINLESS STEEL	Little effect within range of water systems	Not necessary for protection.	Increased bicarbonate may increase corrosion.
COPPER	1. A pH > 7 will minimize uniform corrosion; also uniform corrosion will decrease with increasing pH (6). 2. Pitting corrosion will proceed at pH levels above 7.	1. Soft waters are not corrosive if CO_2 is low (18). 2. Pitting corrosion can occur in hard waters which are cold (5).	Addition of bicarbonate alkalinity may increase corrosion (35, 36)
LEAD	1. A pH of 6-9 is preferred to minimize corrosion (13, 20). 2. A pH of 6.5-7.0 is preferred to minimize corrosion (26).	1. A hardness of 10-100 PPM as CaCO_3 is preferred (26). 2. A hardness of 125 PPM as CaCO_3 is desirable (32).	An alkalinity of 20 PPM is desirable to form a protective film (12).
ALUMINUM	Optimum pH is 7.0-7.5.	1. In general, soft waters are preferred. 2. The preferred concentration is dependent on the period of immersion. 3. CaCO_3 concentration should be approximately equal to the chloride concentration (2).	-
ASBESTOS-CEMENT		pH + Log (Hardness x Alkalinity) should be ≥ 12.0 (3).	
CONCRETE PIPE	pH levels of 7.0 and greater are preferred to inhibit leaching.	Hardness in excess of 16 PPM Ca^{++} is preferred to inhibit leaching.	Alkalinity in excess of 40 PPM as CaCO_3 is preferred to inhibit leaching.
PLASTIC PIPE			-

*Source: J. E. Singley, et al., Corrosion Prevention and Control in Water Treatment and Supply Systems, Pollution Technology Review No. 122 (Noyes Publications, Park Ridge, NJ, 1985), pp 301-308. Used with permission.
 **See table references on pp 54-56.

Table 4 (Cont'd)

MATERIAL	DISSOLVED OXYGEN	CO ₂	TDS
IRON-BASED MATERIALS:			
PLAIN IRON	Corrosivity increases linearly with dissolved oxygen concentrations; however, better protective films are formed at higher dissolved oxygen concentrations.	Carbonic acid is aggressive to iron.	<ol style="list-style-type: none"> 1. Presence of TDS can decrease O₂ and CO₂ content and, therefore, reduce corrosion. 2. An increase in conductivity can increase the range of galvanic coupling or lead to the formation of a less protective Fe(OH)₂ film. 3. The presence of Cl⁻ and SO₄⁼ can increase corrosiveness (23). 4. The presence of Cl⁻ and SO₄⁼ may improve protectiveness of scale (11).
GALVANIZED IRON	Corrosiveness of water increases directly with increased dissolved oxygen concentrations.	Corrosiveness of water increases with CO ₂ concentrations.	<ol style="list-style-type: none"> 1. At levels required for water treatment, Cl⁻ does not increase corrosion (1). 2. At levels above that required for water treatment, Cl⁻ will accelerate corrosion. 3. Corrosion is enhanced with higher neutral salt concentrations (39).
STAINLESS STEEL	<ol style="list-style-type: none"> 1. The presence of dissolved oxygen is necessary for the formation of a protective film. 2. The presence of dissolved oxygen is aggressive and encourages corrosion (14, 29, 33) 	-	<ol style="list-style-type: none"> 1. The presence of SO₄⁼ will inhibit corrosion. 2. The presence of Cl⁻ can cause severe corrosion (severity depends on type of stainless steel) (14, 29, 33).
COPPER	<ol style="list-style-type: none"> 1. Corrosion is negligible in the absence of dissolved oxygen (31). 2. The presence of dissolved oxygen will enhance corrosion, but corrosion or the corrosion rate is not dependent on the dissolved oxygen concentration. 	Dissolved CO ₂ appears to enhance corrosion	Specific effects are difficult to identify.
LEAD	Lower concentrations favor inhibition of corrosion.	Excess CO ₂ may dissolve protective carbonate films and assist corrosion (32).	<ol style="list-style-type: none"> 1. Chlorides should be minimized (31). 2. Ions that form soluble lead salts should be minimized (32).
ALUMINUM	Minimal dissolved oxygen is optimal.	-	<ol style="list-style-type: none"> 1. Chloride concentration should approximate the CaCO₃ concentration. 2. Preferred TDS concentrations are dependent on the period of immersion.
ASBESTOS-CEMENT	-	Low CO ₂ concentrations are preferred.	Possible inhibitory effect of dissolved solids.
CONCRETE PIPE	-	Low CO ₂ concentrations are preferred.	-
PLASTIC PIPE	-	-	-

Table 4 (Cont'd)

MATERIAL	METAL IONS	ORGANIC ACIDS	VELOCITY
IRON-BASED MATERIALS:			
PLAIN IRON	-	Presence of humic acids will inhibit corrosion (30).	Stagnant waters can cause pitting and localized corrosion; optimum velocity occurs between 1 fps and 8-15 fps.
GALVANIZED IRON	Copper even at low concentrations will increase zinc corrosion; the presence of copper is often a main factor in the corrosion of galvanized iron.	Presence of humic acids improves protective deposit formation and reduces corrosion (40).	Velocity differences produce little effect (4).
STAINLESS STEEL	-	-	1. Stagnant waters are corrosive. 2. High velocity can be tolerated.
COPPER	A low concentration of Fe^{++} (0.05-0.5 PPM) may inhibit corrosion.	An unknown organic corrosion inhibitor exists in surface water but not groundwater; this natural inhibitor is probably of high molecular weight and may be an organic acid (5).	1. Some flow is required to form protective Cu_2O film. 2. Velocity in excess of 5 fps can cause impingement attack (19).
LEAD	-	Minimize occurrence of organic acids whose lead salts are soluble (32).	Water should be running, not standing (27).
ALUMINUM	Metal ions, especially copper, tin, nickel, and mercury should be minimized (15, 28).	-	Prefer a minimum velocity of 8 fps (15).
ASBESTOS-CEMENT	Fe^{++} can precipitate to form a protective coating to inhibit calcium leaching (3).	-	Water should be running, not standing (24).
CONCRETE PIPE	Fe^{++} can precipitate to form a protective coating to inhibit calcium leaching (3).	-	Water should be running, not standing (24).
PLASTIC PIPE	-	-	-

Table 4 (Cont'd)

MATERIAL	TEMPERATURE	COMMENTS
IRON-BASED MATERIALS:		
PLAIN IRON	Aggressiveness of water increases with temperature up to $\approx 80^{\circ}\text{C}$; at higher temperatures the aggressiveness decreases (37).	Effects of any single variable are influenced by other parameters, especially the interrelation between pH, temperature, dissolved oxygen, alkalinity, hardness, TDS, and velocity.
GALVANIZED IRON	Increasing temperature will increase corrosion (16).	Interrelation exists between pH, hardness, temperature, alkalinity, TDS, plus organic acids or other stabilizing agents like phosphates or silicates.
STAINLESS STEEL	Increased water temperature above 25°C results in a significant increase in pitting susceptibility.	Different types of stainless steel have different corrosive tendencies. Cl and dissolved oxygen are two most important chemical factors in stainless steel corrosion.
COPPER	Temperature effects are complex but usually not a major factor.	Copper concentration generally does not exceed 5 PPM--may be limited by solubility of reaction product.
LEAD	Temperatures 20°C and less are preferred for corrosion control (26).	-
ALUMINUM	Prefer higher temperatures of 40°C and up (15).	Aluminum corrosion is highly dependent on the period of immersion.
ASBESTOS-CEMENT	-	-
CONCRETE PIPE	-	Corrosion control is practiced by minimizing the dissolution of Ca^{++} , often by regulating CaCO_3 stability components.
PLASTIC PIPE	-	1. Corrosion products that have been found are thought to leach from solvents used for joints. 2. No variable cause-effect testing results are available.

3 CORROSION-INHIBITING CHEMICALS USED FOR DRINKING WATER TREATMENT

A corrosion inhibitor as defined by the National Association of Corrosion Engineers (NACE), is "a substance which retards corrosion when added to an environment in small concentrations."⁵ This definition is rather broad and includes materials that would be inappropriate and unacceptable for use in drinking water treatment. This chapter outlines the major types of water quality control chemicals used as corrosion inhibitors in drinking water. It describes these chemicals' characteristics, advantages, and disadvantages, and how their effectiveness depends on water characteristics, inhibitor dosage, and the distribution system. (More details can be found in the sources listed in the reference section.)

Much research has been conducted in the area of corrosion inhibition in drinking water systems. However, due to the complex nature of the mechanisms involved, results of studies often contradict each other or accepted theory and often pertain only to highly specific test cases.

The underlying theory behind corrosion control by addition of inhibitory substances is quite simple. An inhibitor reacts with the water or ions in the water to form a protective coating that shields the pipe material from the corrosive action of the water. There are three general classes of inhibitors commonly used for drinking water treatment. They include pH control for calcium carbonate precipitation, inorganic phosphates, and sodium silicates. The extent to which these inhibitors provide corrosion protection depends on a number of factors, including water characteristics, plumbing materials, inhibitor dosage, and flow characteristics of the water system.

Types of Corrosion Inhibitors

pH Control for Calcium Carbonate Precipitation

It has long been recognized that precipitation of calcium carbonate is an effective form of corrosion control. The reactions of calcium ions with carbonate ions form a solid protective coating of calcium carbonate. In addition, other metal ions present in water, whether present naturally or as products of corrosion, are capable of forming complexes and precipitates with carbonate ions when their solubility products are exceeded. Metal ions such as iron, copper, zinc, and lead will form protective coatings when precipitation of a metal-carbonate complex occurs. Calcium carbonate forms a rather solid coating that has good adhering characteristics, enabling it to stick to the interior of metal pipes. Of the other carbonates formed, zinc carbonate forms the most dense coating, providing good protection against corrosive water. The most effective protective coatings form very slowly, providing a hard, impenetrable coating.

The amount of calcium carbonate formed and the rate at which the coating is deposited are determined by the water characteristics. The water characteristics most affecting the precipitation of calcium carbonate are pH, alkalinity, calcium concentration, chloride concentration, and sulfate concentration. For precipitation to occur at all,

⁵"NACE Glossary of Corrosion Terms," *Materials Protection*, Vol 4, No. 1 (1965), pp 79-80.

the water must be oversaturated with respect to calcium carbonate. Empirical results have shown that the optimum degree of oversaturation is in the range of 4 to 10 mg/l* as calcium carbonate.⁶ This range allows for a slow rate of precipitation and the formation of a hard coating. Calcium and alkalinity concentrations should be greater than 40 mg/l as calcium carbonate, pH in the range of 6.8 to 7.3, and the ratio of bicarbonate alkalinity to chloride + sulfate concentration should be at least 5:1 to insure the formation of a good protective coating.

Because corrosive waters are generally low in alkalinity and pH and often high in carbon dioxide, additions must be made to the water to alter its characteristics to promote the formation of protective coatings. Chemicals can be added that increase alkalinity, pH, and calcium concentration, and reduce the carbon dioxide concentration. (All these factors are interrelated.) The choice of the method depends on economic factors and on the characteristics of the water to be treated. For waters low in alkalinity and calcium, lime can be added to increase alkalinity and calcium concentration simultaneously. When carbon dioxide is inexpensive, it can be made to react with lime or limestone to produce a concentrated solution of calcium bicarbonate, which can then be mixed with the water to be treated. If this method is used, additional lime may be required to increase the pH to the optimal range. Other methods have been employed that entail passing the water through a porous bed of crushed limestone; however, this method often involves prohibitively long contact time, and pH values above 6.5 are seldom achieved. For low alkalinity waters, lime appears to be the most effective and least expensive method to increase alkalinity, calcium, and pH.

Many other factors affect the degree to which calcium carbonate precipitation is an effective corrosion control method. These include water temperature, plumbing materials, flow velocity, dissolved oxygen content, and concentration of dissolved solids. Temperature affects the solubility of calcium carbonate and the rate at which chemical reactions occur. As the water temperature increases, calcium carbonate becomes less soluble. For example, water that is just saturated with respect to calcium carbonate at 25 °C will tend to precipitate calcium carbonate as the temperature rises. Reactions of water constituents with plumbing materials can result in unwanted or harmful products. For example, in lead pipes, toxic lead corrosion products may form if pH adjustment is used without sufficient carbonate and alkalinity. Waters in the eastern and northwestern portions of the United States are generally too soft to allow for pH adjustment alone and require additions to increase alkalinity and hardness. The flow velocity in the water system can affect the precipitation of protective coatings. Water velocities should be greater than 1 ft/s to ensure an even distribution of calcium carbonate. Dissolved oxygen indirectly affects the strength of the protective coatings as well. Because the strength of the coating is increased by the presence of ferric oxides, it is suggested that a minimum of 5 mg/l of oxygen be present. The dissolved oxygen content of a water must be carefully controlled because as oxygen content increases the rate of corrosion also increases due to stimulation of the cathodic reaction. Other dissolved materials in the water affect the solubility of calcium carbonate by increasing the ionic strength of the water and thus increasing the solubility of calcium carbonate.

*Metric conversion factors are given on p 52.

⁶R. L. Sanks, *Water Treatment Plant Design for the Practicing Engineer* (Ann Arbor Science, Ann Arbor, MI, 1978).

Inorganic Phosphates

Three basic types of phosphates are used as corrosion inhibitors for drinking water systems. (1) Orthophosphates ("crystalline phosphates"), specifically sodium orthophosphate, are often used in Germany, either alone or with zinc.⁷ (2) Polyphosphates ("glassy phosphates") are formed from the combination of a caustic soda or soda ash with phosphoric acid. They can exist in many forms depending on how they are manufactured. (3) Bimetallic phosphates are usually a combination of 10 percent zinc with 90 percent polyphosphate. Other types of phosphates are used, including zinc orthophosphates and other phosphate blends.

Phosphates, when added to water, form negatively charged particles.⁸ To form a protective coating, the negatively charged particles form complexes with divalent cations, creating colloidal particles, which then migrate toward the cathode (the pipe) and form a protective coating on the pipe's interior. Phosphates can form complexes with many divalent cations. Ferric pyrophosphate and iron-calcium metaphosphate compounds have been observed as components of protective coatings. However, calcium appears to form the most effective corrosion-inhibiting complex.

The effectiveness of phosphates for corrosion control depends on the phosphate concentration, flow velocity, pH, temperature, calcium concentration, iron concentration, and carbonate concentration. The various types of phosphates respond differently to different water characteristics. As with any of the protective-coat-forming corrosion inhibitors, flow velocity affects the quality of the coating. The general rule is that a flow velocity greater than 1 or 2 ft/s should be maintained to form an even coating: as the velocity increases the quality of the coating increases as well. More turbulent flow through a water pipe will more evenly precipitate a protective coating and will promote the formation of a harder, more adherent coating by shearing off the less adherent precipitation products. In water systems with intermittent flow patterns, this type of inhibitor is ineffective. As with calcium carbonate precipitation, temperature affects both the solubility of phosphate precipitates and the rate at which complexes form. The remaining factors mentioned above have different effects depending on the type of phosphate used. The polyphosphates appear to perform better at pH values of 7 or less and are affected by the calcium concentration. A calcium to phosphate ratio of at least 0.2 should be maintained and a ratio of 0.5 or more is preferred. In contrast, the orthophosphates appear to be more effective in more alkaline waters than the polyphosphates. Bimetallic phosphates seem to be most effective in more mineralized and harder waters, are more effective at lower dosages than the polyphosphates, and can extend the pH range in which polyphosphates are most effective up to around 8.0. The presence of iron in the water seems to promote the formation of calcium-iron phosphate complexes which can also precipitate to form protective coatings.

Sodium Silicates

Sodium silicates have been used in water systems as corrosion inhibitors for over 50 years. They exist in dry form ("water glass") or in liquid solutions. In solution they exist in varying proportions of sodium oxide and silica. The availability of various ratios of sodium oxide to silica makes silicates suitable for use with various water conditions and piping material.

⁷Internal Corrosion of Water Distribution Systems (American Water Works Association [AWWA] Research Foundation, Denver, CO, 1985).

⁸Internal Corrosion of Water Distribution Systems.

In the proposed silicate inhibition mechanism, a silica gel forms when the silicate is added to the water,⁹ then corrosion products such as iron, zinc, magnesium, calcium, and other metals present in the water adhere to the gel, forming a protective film. The silica gel will not form a protective coat alone, because some corrosion is required before a protective coat is formed to provide the corrosion products that adhere to the gel.

The factors most affecting silicate inhibition are flow velocity, temperature, pH, hardness, presence of corrosion products, dissolved solids concentration, bicarbonate concentration, and chloride concentrations. Temperature and velocity effects are similar to those on phosphate and calcium carbonate inhibition. The effects of bicarbonate and pH are closely related to each other. When silicates are used, the presence of bicarbonate has been shown to increase the rate of corrosion; therefore, because bicarbonate and pH are related, waters with low pH values are best suited for silicate treatment. Water hardness, chloride concentrations, and dissolved solids concentration affect the dosages required for effective inhibition. The dosage aspects of corrosion inhibitors will be discussed later in the chapter.

Effects on Various Plumbing Materials

Lead

With lead pipe, the major concern is the presence of lead in drinking water, but not the corrosion of pipes.¹⁰ Calcium carbonate can prevent the uptake of lead into the water by forming a protective coating that prevents the water from contacting the lead pipe. Recent studies have shown that polyphosphates and silicates do not reduce the solubility of lead in water and thus are ineffective for controlling lead concentration. Orthophosphates have been shown to form insoluble compounds with lead that can form a layer on the pipe surface, reducing soluble lead concentrations.

Copper

Copper pipes are affected by both general corrosion and by pitting or localized corrosion. The formation of protective calcium carbonate coatings will prevent both types. Of the silicate and phosphate inhibitors, the most effective seems to be an orthophosphate-polyphosphate mixture. Orthophosphates have exhibited some degree of corrosion control when used alone but are much more effective in combination with polyphosphates. Silicates seem to have little effect on corrosion of copper. This small effect seems to be associated only with the increase in pH when silicates are added. Pitting corrosion has not been shown to be affected by the use of phosphates or silicates.

Galvanized Steel

Orthophosphates are the most effective for reducing the corrosion rate of the protective zinc coating in galvanized steel. Polyphosphates have been shown not to affect the corrosion rate of the zinc coating. Silicates will only prevent general corrosion of the zinc coating in very high concentrations.

⁹Internal Corrosion of Water Distribution Systems.

¹⁰Internal Corrosion of Water Distribution Systems.

Use Of Inhibitors

A corrosion control program using inhibitors usually consists of a period of pretreatment in which concentrations are high enough for protective coatings to form, then a period of gradual decrease in concentration over time, and then a steady state concentration sufficient to maintain the protective coating.¹¹ Dosage requirements for both the pretreatment stage and maintenance stage depend on water characteristics such as chloride concentration, dissolved solids concentration, and water temperature. The type of inhibitor used depends on the water characteristics and the plumbing material, as described in this chapter. In general, as water temperature, chloride concentration, and dissolved solids concentration increase the amount of inhibitor required also increases.

One example of a treatment schedule used for a polyphosphate inhibitor consisted of one day feeding at concentrations of 20 to 40 mg/l, reduction over one week to 10 mg/l, followed by reduction over one month to 5 mg/l, and subsequent reduction over one additional month to 1 to 2 mg/l. Bimetallic phosphates require dosages of about half of that required for the above hexametaphosphate treatment. A manufacturer of zinc orthophosphate recommends feeding at 3 mg/l for three days followed directly by reduction to a maintenance dosage of 0.3 mg/l. Silicates require pretreatment with between 8 and 20 mg/l for 3 to 4 weeks followed by maintenance dosage of 5 to 10 mg/l. During the pretreatment stage it is very important to keep the water velocity above 0.5 ft/s and preferably at 2 ft/s. For systems with dead ends, this means water lines must be flushed regularly or continuously to maintain sufficient flow velocity during the pretreatment stage.

¹¹J. E. Singley, et al.

4 MONITORING TECHNIQUES FOR CORROSION CONTROL

A number of techniques for monitoring the effects of corrosion exist, ranging from very inexpensive methods such as customer complaint logs to relatively expensive and more technical methods of electrochemical rate measurement.^{1 2}

The choice of which technique to use depends on the objectives of the corrosion study being undertaken. For instance, one might be interested in determining the corrosiveness of one water compared to another water, the rate of corrosion in a water distribution system, the concentration of corrosion byproducts in a water supply, or the effectiveness of various corrosion control methods. Each of these objectives might be best handled with different monitoring methods or combinations of different methods. The purpose of this chapter is to outline the various monitoring methods and to describe their advantages and disadvantages in relation to the objectives of the corrosion study being undertaken.

There are two general classes of corrosion monitoring methods--direct and indirect. The indirect methods include customer complaint logs, corrosion indices, and water sampling and chemical analysis. These methods do not measure corrosion rates; however, the data obtained can be interpreted and compared to show trends or changes in the system. The direct methods include examining scale or pipe surface and measuring rates.

Indirect Methods

Customer Complaint Logs

Complaints by customers are typically the first indication of a corrosion problem. Customer complaints can arise for a number of reasons, not all of which are caused by symptoms of corrosion. If good records of complaints are kept, however, trends can be seen that may indicate a corrosion problem. A complaint map shows the water distribution system with codes to indicate the location, frequency, and type of complaints received. Such a map can be useful in determining if a problem exists and where it may be located. Customer surveys may also be used to get the same information more quickly than compiling records of customer complaints. These methods are quite inexpensive and, depending on how the data is used, can be very effective as a first step in a corrosion control program.

Corrosion Indices

Many corrosion indices have been developed to determine and predict whether a water is corrosive, but they have had only limited success. These indices include, the Langelier Index, the Calcium Carbonate Precipitation Potential, the Aggressiveness Index, the Ryznar Stability Index, Riddick's Corrosion Index, and McCauley's Driving Force Index. Perhaps the most widely used of the corrosion indices is the Langelier Index (LI). It is based on the effect of pH on the solubility of calcium carbonate.

^{1 2}J. E. Singley, et al.; *Internal Corrosion of Water Distribution Systems*.

Water parameters needed to calculate the LI are total alkalinity, calcium concentration, total dissolved solids (or, more precisely, ionic strength), pH, and temperature. With these parameters it is possible to calculate the pH at which a water is in equilibrium with solid calcium carbonate, which is known as pH_s . The LI is simply calculated as the difference between the actual pH of the water and the value of pH_s . A positive value means the water will tend to precipitate calcium carbonate. A negative value indicates that the water will tend to dissolve calcium carbonate. A value of zero, by definition, indicates that the water is in equilibrium with calcium carbonate. This index is useful for estimation purposes, but its use is limited by temperature and ionic strength considerations. The other indices mentioned are similar in theory and have similar limitations; however, they can be used as quick estimates of the corrosive tendencies of a particular water and require only simple calculations.

Sampling and Chemical Analysis

Chemical analysis of water samples can be a very useful method of determining whether a corrosion problem exists. Because corrosion is affected by the chemical composition of the water, it may be useful to know what constituents in the water may be accelerating or inhibiting the rate of corrosion. A chemical analysis can show where there are higher than normal concentrations of corrosion products, and by sampling at various points throughout a water system, locations of corrosion problems can be determined. Chemical analyses are also useful in showing whether or not a corrosion control program is working as predicted. A sampling program must be carried out on a regular basis to insure reliable data collection. Proper sampling techniques are crucial. Water samples should be taken without adding any gas which may react with or remove any of the water constituents. Analyses should be made as quickly as possible to insure that the sample being analyzed is an accurate representation of the water in the system.

Direct Methods

These methods monitor corrosion by measuring corrosion rates directly. They include experimentation, examination of metal samples, and electrochemical analysis. The procedures are quite simple, with fairly straightforward calculations, but sometimes the experimental apparatus is expensive. Great care must be taken, however, in preparing metal samples and the apparatus to insure accurate measurements of corrosion rates. The following sections discuss various direct methods.

Inserts In Pipe Loops And Plumbing Systems

To insure accurate data collection, four criteria must be met: (1) the metal samples must be representative of the material in the plumbing system, (2) the water used must be of the same quality as that of the system being studied, (3) the flow velocity, flow pattern, and stagnation time should be similar to those of the full scale system, and (4) the duration of the test must be long enough to insure formation of any scale that may affect the rate of corrosion. (Table 5 shows rough estimates for times required [in months] for accurate data collection).

Table 5
Estimated Duration (Months) Required for Corrosion Tests*

Material	Comparison of Uniform Corrosion Rates or Metal Leaching	Comparison of Inhibitors		Pitting
		New Pipe	Old Pipe	
Iron	12-24	3-6	12-24	12-24
Copper	3-6	1-3	3-6	12-36
Galvanized Iron (Zinc)	3-6	1-3	6-12	12-36
Lead	6-12	2-6	6-12	
Asbestos Cement	18-24	6-12	12-18	
Mortar Lining	24-36	12-24	24-36	

*Reprinted from *Internal Corrosion of Water Distribution Systems*, by permission. Copyright © 1985, American Water Works Association.

It is necessary to use metal samples of the same material used in the full scale system in such a way that the flow pattern around the sample is similar to that of the full scale system. Therefore, insertion of flat metal samples (coupons), for example, will not give flow patterns similar to those in a circular pipe section. Circular samples of actual pipe material inserted into a loop system or plumbing system will insure more accurate representation of the flow patterns in the full scale system.

Illinois State Water Survey (ISWS) Machined Nipple Test

This method is described in detail in ASTM Standard D-2688-83, Method C.¹³ A short length of the actual pipe material, encased in a polyvinyl chloride sleeve, is inserted into the pipe system using pipe unions, so the sample can be removed for analysis. A bypass line must also be inserted to allow for water flow around the sampling area when the specimen is not in place. The specimen holder must be designed to insure smooth flow through the pipe sample. Figures 1 and 2 show the details of the specimen and PVC sleeve used in this method.

It is recommended that the sample be a 1 m length of straight pipe. If more than one sample is used in series and one is removed for analysis, a plastic insert should be put in place to insure that the flow is not disturbed for the samples farther down stream. The analysis consists of removing any scale that has formed on the interior of the sample and weighing the sample to determine the amount of pipe material lost to corrosion. Once weighed, the sample can be cut open so the interior

¹³ ASTM Standard D-2688-83, "Standard Test for Corrosivity of Water in the Absence of Heat Transfer (Weight Loss Methods)," *ASTM Annual Book of Standards* (American Society for Testing and Materials [ASTM]).

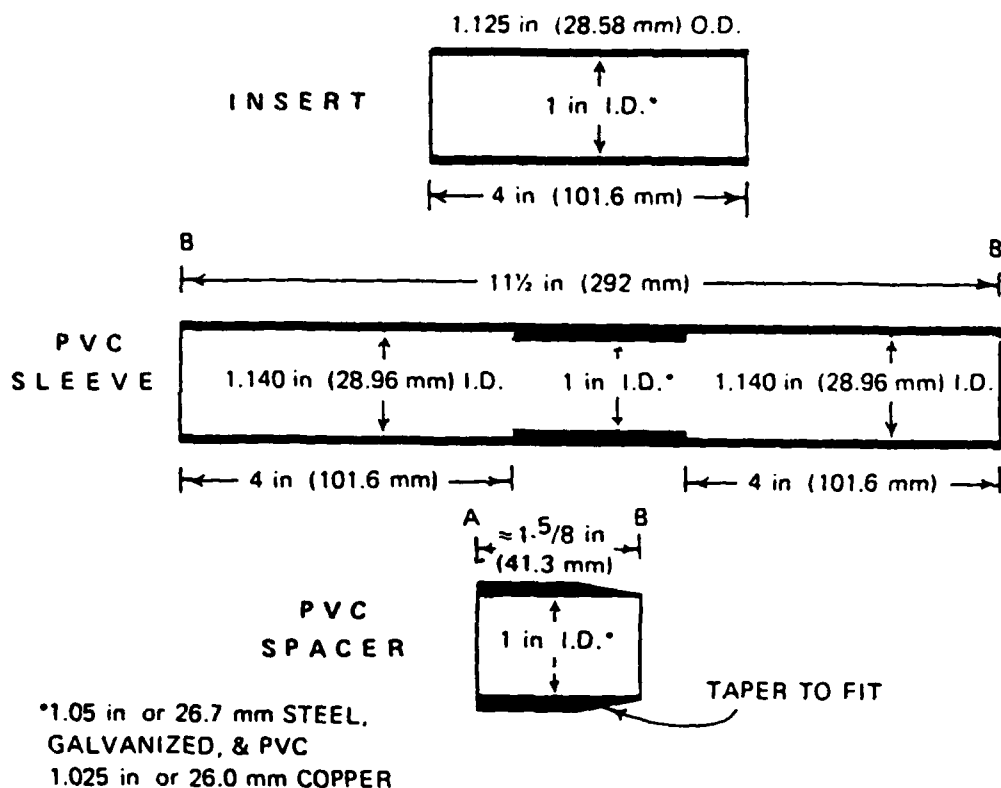


Figure 1. Schematic of ISWS corrosion tester. (Reprinted from *Internal Corrosion of Water Distribution Systems*, by permission. Copyright © 1985, American Water Works Association.)

surface can be examined for irregular corrosion patterns and pitting. Corrosion rates are usually expressed in units of mass per area per time; thus the calculation of corrosion rate would be

$$\text{corrosion rate} = (\text{g/m}^2/\text{day}) = W/A/T \quad [\text{Eq 1}]$$

where W is the mass removed by corrosion, A is the internal surface area from which the material was removed, and T is the duration of the test. Other units are used for corrosion rates as well, the most common being corrosion velocity, which is usually expressed in $\mu\text{m}/\text{yr}$.

The Metal Uptake Test

This method is used when corrosion rates are to be determined by measuring the corrosion products concentration. Since the machined nipple test involves analysis of a pipe sample, it cannot be used to determine the concentrations of corrosion products in the water because of insufficient contact time between the water and the pipe sample. Instead, this method uses a recirculating loop system constructed entirely from the pipe material being studied. This insures adequate contact time between the water and the

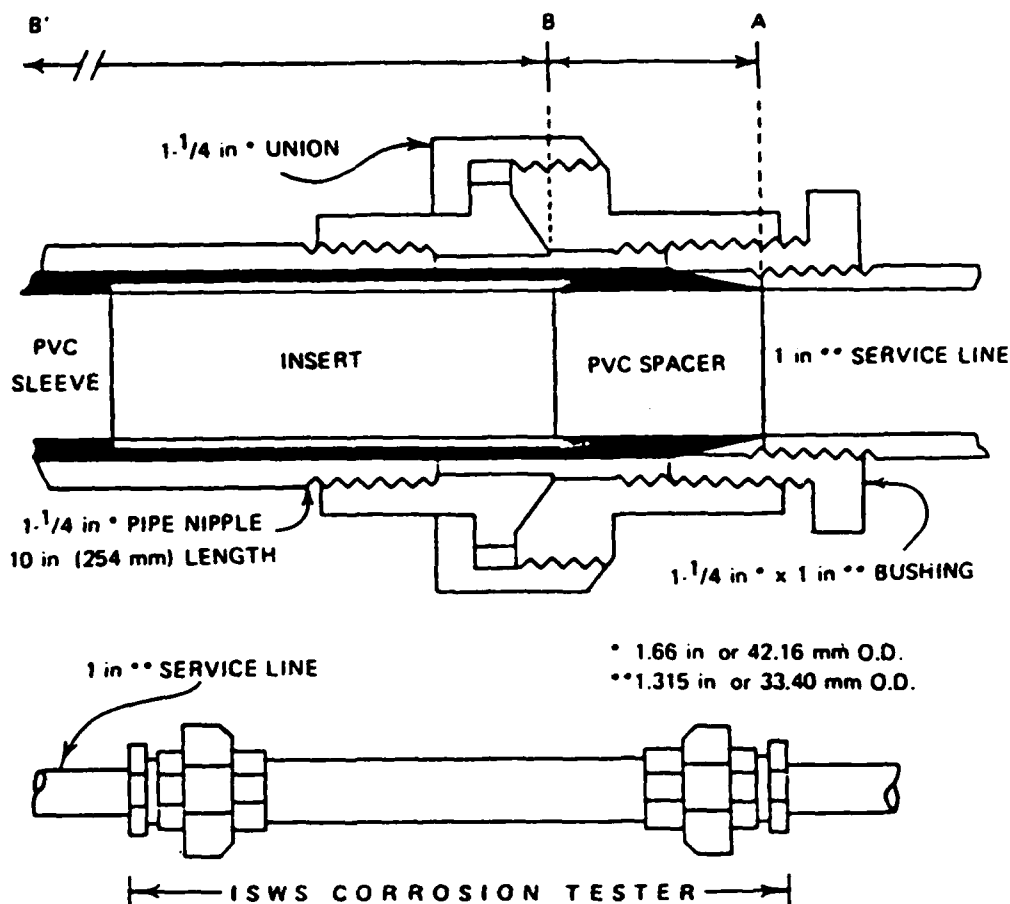


Figure 2. Cross-section of assembled ISWS corrosion tester. (Reprinted from *Internal Corrosion of Water Distribution Systems*, by permission. Copyright © 1985, American Water Works Association.)

pipe material and allows high enough concentrations of corrosion products to develop so they can be accurately measured by analytical methods. The apparatus is pictured in Figures 3 and 4.

Before the test begins, the system is flushed with fresh water for 30 minutes. Once the flushing is completed, the system is changed to the recirculating mode, samples are taken, and water is added equal to the amount removed in the sample. The water samples are then analyzed for metal concentration. The test is usually run for 30 minutes, and the results obtained represent the instantaneous status of the corroding metal. A plot of metal concentration versus time is made, from which the rate of metal uptake in the water is determined. To determine the rate of metal uptake it is necessary to know the internal surface area of the pipe used in the test and the total volume of the closed loop system. The slope of the concentration versus time plot, in units of mass per volume per time, is multiplied by the system volume and divided by the surface area of the system to give the metal uptake rate in units of mass per area per time.

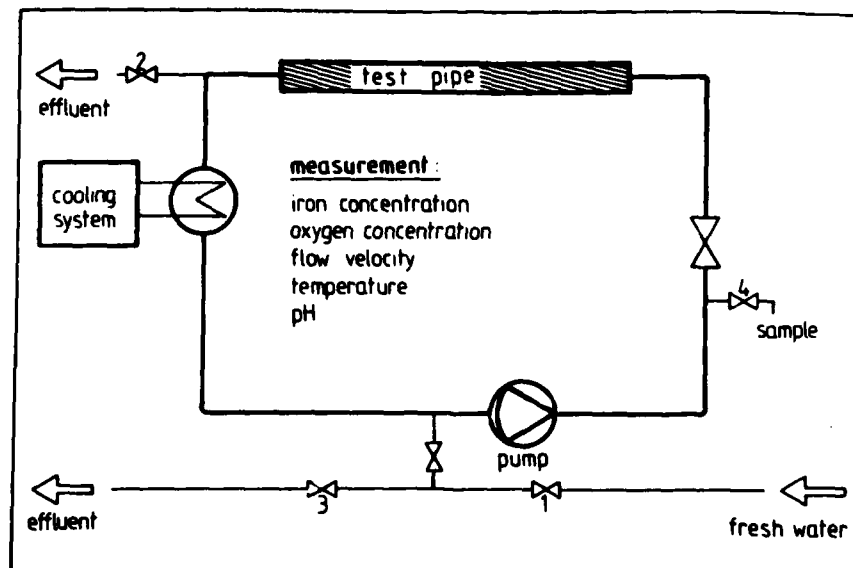


Figure 3. Schematic diagram of metal uptake test loop device. (Reprinted from *Internal Corrosion of Water Distribution Systems*, by permission. Copyright © 1985, American Water Works Association.)

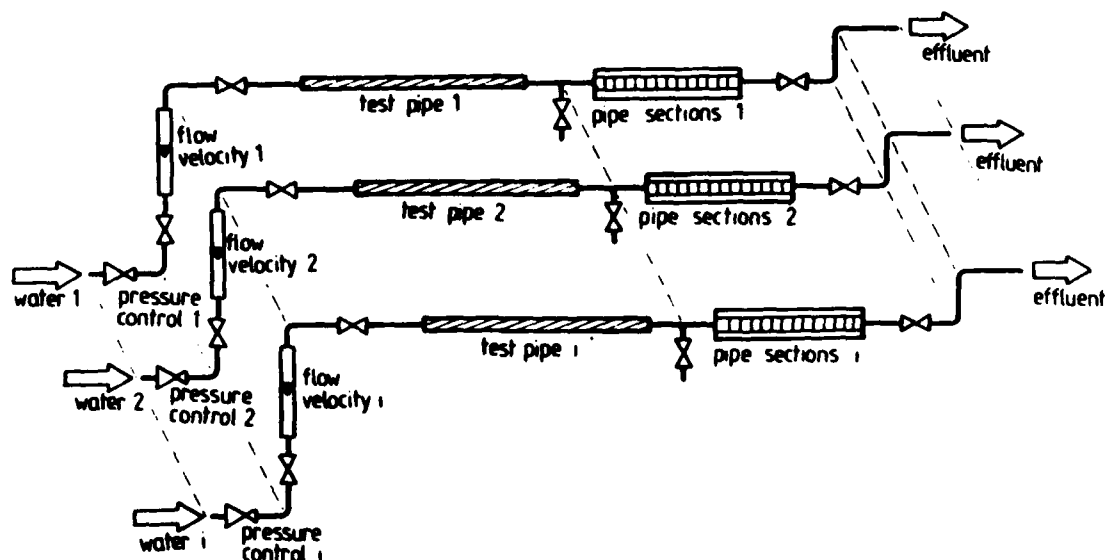


Figure 4. Scheme of the test pipe rig. (Reprinted from *Internal Corrosion of Water Distribution Systems*, by permission. Copyright © 1985, American Water Works Association.)

Corrosion Coupon Testing

In this method, an accurately weighed pipe specimen, a "coupon," of the same material as the pipe system being studied is inserted into a section of the actual pipe system for a period of between 90 to 180 days. The coupon, usually a flat bar, is attached to a plug, which is then screwed into the pipe system and left for the duration of the test. At the end of the test period, the coupon is removed and weighed to determine the amount of material lost to corrosion. This method is somewhat less involved than the two previously described methods and requires much less analysis time and money (although the test duration is quite a bit longer in this method). The results obtained from this method, however, may not be as accurate because the metal coupon is not a circular pipe section and the flow patterns around the coupon are not at all similar to those around the actual pipe system.

Electrochemical Methods

The methods of coupon testing previously described are rather costly and time-consuming. This fact has led to the development of electrical instruments that can quickly measure corrosion rates using electric resistance, linear polarization, and galvanic current techniques. These instruments are particularly attractive because they can be made as portable instruments for use in field operations for instantaneous rate measurement.

Electric Resistance Measurement

This method (which is really electrical rather than electrochemical) is rather straightforward and easy to use. It consists of a low resistance Kelvin bridge circuit constructed entirely from the same material as the pipe being monitored, except for the slide wire. As the probe corrodes, its cross-sectional area is reduced and its resistance is increased. The instrument measures the change in resistance of the probe with time, which can be recorded manually or automatically, yielding a plot of resistance versus time. From this data, with the proper conversion factors supplied by the manufacturer, the corrosion rate is determined from Equation 2:

$$CR = ([D2 - D1] \times PF \times 0.365)/T \quad [Eq 2]$$

where CR is the corrosion rate in mils per year, D1 and D2 are the initial and final (respectively) dial readings from the instrument in microinches, PF is the probe factor supplied by the manufacturer, and T is the time in days of the test. These instruments are easy to use, reliable, and fairly economical; however, they give no indication of pitting corrosion, and data from scale-covered specimens may be hard to interpret.

Linear Polarization

These instruments are based on the principle that a linear relationship exists between small shifts in electrochemical potential or polarization and the corrosion rate of a metal. They consist of either two or three probes through which a small direct current is passed, creating a 20 millivolt electrochemical polarization of the probes. They provide a direct readout of corrosion rate and indicate whether pitting is occurring. The theory behind these instruments is rather involved and beyond the scope of this

report. The details of the theory can be found in most corrosion science texts (e.g., Fontana and Greene [1978]).¹⁴

Galvanic Current Method

These instruments use a zero-resistance ammeter to measure corrosion of dissimilar metals. They are useful in measuring galvanic and ground currents, which in some cases are related to internal corrosion.

The electrochemical instruments provide for quick, convenient, and often portable means by which corrosion rates can be measured. They are fairly economical and require no experimental apparatus. They are also very well suited for permanent monitoring of pipe corrosion in situations where corrosion can lead to expensive or catastrophic failure.

¹⁴M. G. Fontana and N. D. Greene, *Corrosion Engineering* (McGraw Hill, New York, 1978).

5 DEVELOPMENT OF A PIPE LOOP SYSTEM FOR INHIBITOR EVALUATION

It is evident, from literature available on the corrosion phenomenon in water utilities, that the nature of corrosion and possible corrosion control alternatives are extremely complex. Defining the corrosiveness of a water using a universal corrosion index or parameter is not feasible at this time. Instead, it appears that corrosion control can only be accomplished through a comprehensively applied program on a case by case basis.¹⁵

The commonly used techniques and apparatus for corrosion detection, control, and monitoring have been presented in Chapters 3 and 4. A number of corrosion measurement techniques are less applicable because they are short-term and do not properly take into account the effects of slowly accumulating scales.

Although a large data base is available in the literature, often the data may not be useful for comparing the corrosivity of various waters and the effectiveness of control measures for these waters. Many times it is reported that a particular corrosion control treatment works in a specific water utility but did not work in another water system with similar water characteristics. A part of the problem may be inconsistencies in monitoring procedures. For example, both coupons and pipe inserts have been used as specimens for determining effectiveness of measures. However, the results obtained using coupons may not be comparable to results obtained using pipe inserts. This is due to the difference in the shape of the specimens and the resulting differences in water flow characteristics during exposure. Further, other influences may not have been taken into account. Factors such as temperature and velocity of water are seldom considered in evaluating and reporting the corrosion characteristics of a specific water utility. The effect of a particular chemical varies with the water characteristics. These in turn vary with the seasons. Many times, measurements assume the water quality is constant, which is not necessarily the case.

Pipe Loop System Design

To determine the effect of various chemical inhibitors, inhibitor dosage rates, or water quality on the corrosion of piping materials occurring in public water supplies, a standard testing procedure is needed to minimize extraneous influences. To insure that the data gathered by such a procedure can be used for meaningful comparisons, the water quality must be closely controlled and experiments must be carefully designed. The design of the USA-CERL pipe loop system (Figures 5 and 6) makes both those efforts easier; at the same time it simulates conditions in an actual distribution system, as closely as possible. The design's standard pipe configuration will be usable at most installations. The design was a compromise among several objectives: maintaining the water velocity within a range found in distribution systems, restricting the physical dimensions of the loop to a practical size, and limiting water usage at test locations where water reuse was impractical.

¹⁵Singley, et al.

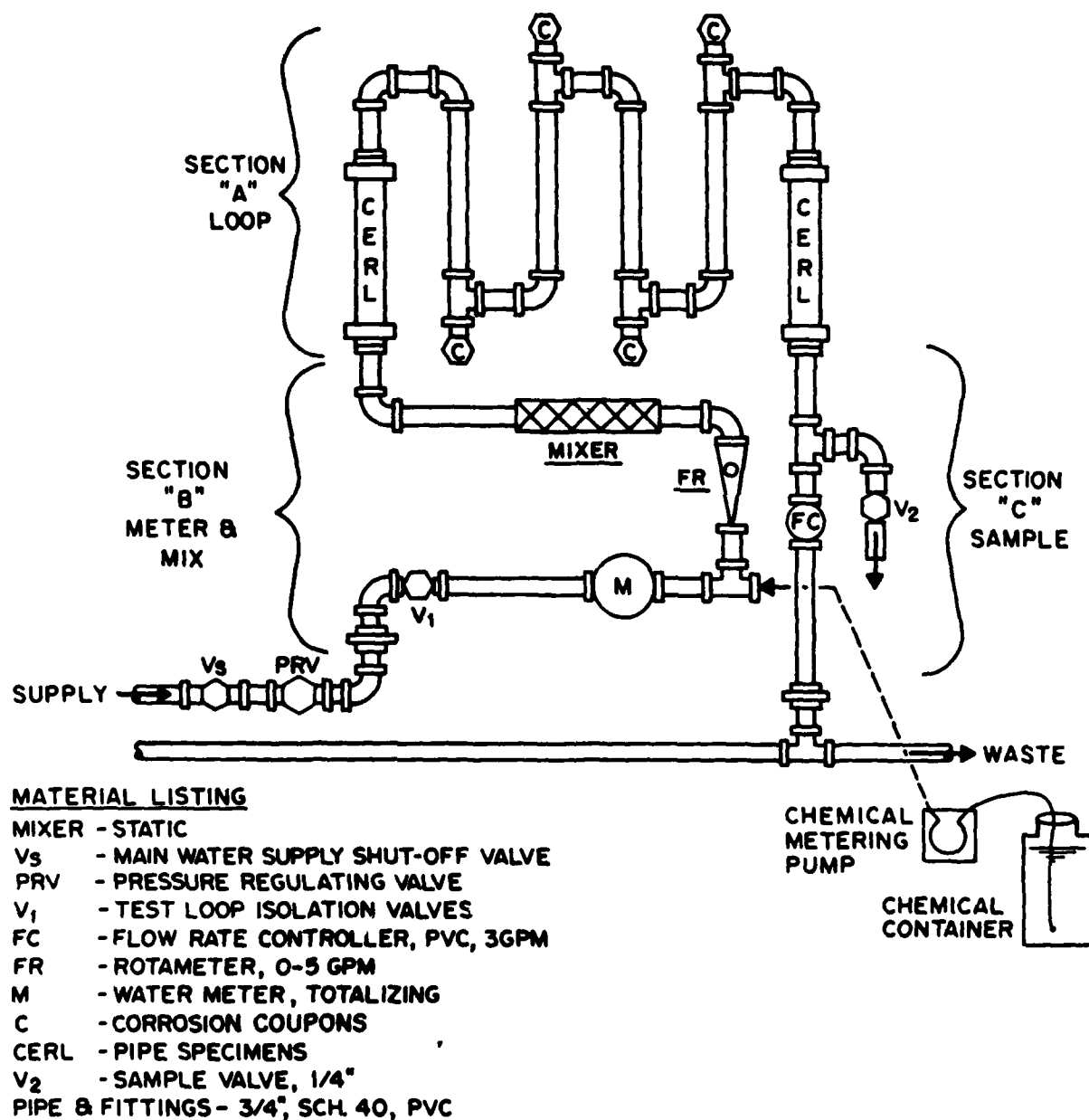


Figure 5. Schematic of USA-CERL pipe loop system.



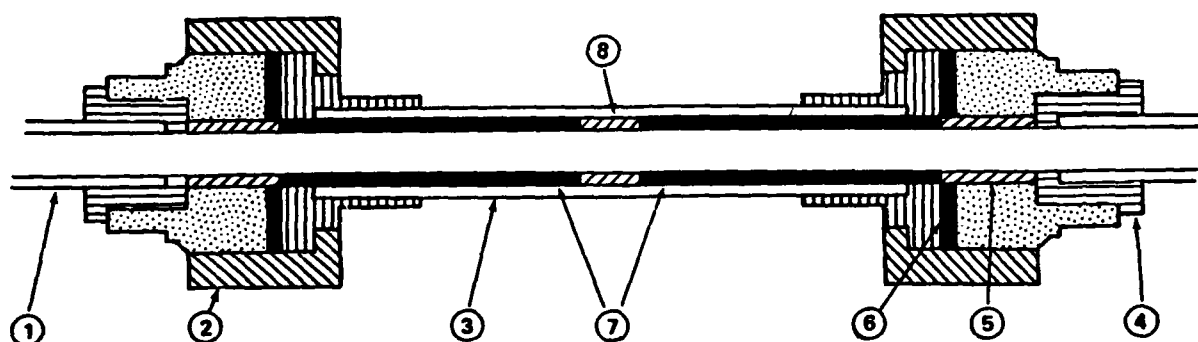
Figure 6. Assembled pipe loop system.

Features

The test loop was constructed of polyvinyl chloride (PVC) and chlorinated polyvinyl chloride (CPVC) pipe and fittings with schedule 40 pipe, and 3/4-in. nominal pipe size. These materials were readily available and had suitable characteristics. This design eliminates all metallic components, except for the corrosion specimens, and electrically isolates the corrosion specimens from one another. The test loop was oriented vertically to minimize the amount of suspended matter deposited on the exposed surfaces of the corrosion specimens. A flow controller (FC), flow rate meter (FR), and regulating valves (V1) were provided to maintain the flow rate through the loop at desired values during normal test conditions. If fluctuating water pressures occurred, a pressure regulating valve (PRV) was used on the inlet piping of the test loop. A totalizing water meter (M) was also included in the design to verify water usage information during monitoring intervals. A chemical container, chemical metering pump, and static mixer were added to the loop to study the effects of selected corrosion inhibitors on the corrosivity of a particular water supply. The continuous flow of both water and inhibitor insured that constant inhibitor concentrations were in contact with the corrosion specimens at all times. A sampling valve (V1) was installed in the loop to collect water samples periodically for chemical analysis and to verify inhibitor concentrations.

This design allows two measurement methods: weight loss of a pipe insert and weight loss of a metal coupon. Both are discussed in Chapter 4 and specified in detail in ASTM Standard D-2688-83. With the pipe loop system, these methods can be used simultaneously on multiple specimens. Four coupon and four pipe insert specimens can be accommodated by the test loop, so that different materials can be studied during the same exposure period, duplicate specimens can be used for statistical evaluation, or the planned interval exposure procedures described by Wachter and Treseder¹⁶ can be carried out. Both coupon and pipe specimens were included so any differences in corrosion occurring on pipe walls could be compared to the corrosivity of the bulk water.

The USA-CERL corrosion tester (Figure 7) was developed because the ASTM Standard D-2688-83 Method C corrosion tester could not be incorporated into the USA-CERL's standard test loop due to incompatible size and construction materials. The new USA-CERL design (constructed entirely of PVC) eliminates the sleeve used in the ASTM design, reduces fabrication time, and, with its uniform dimensions, allows corrosion testers to be interchanged. Streamline flow is maintained through the tester to simulate



- ① 3/4" PVC service line
- ② 1" union, PVC, socket type
- ③ 1 x 10" pipe nipple, PVC, Sch. 40
- ④ 1 x 3/4" reducing bushing, PVC, socket
- ⑤ 3/4" PVC spacer, Sch. 40, O.D. reduced 0.015"
- ⑥ Union gasket
- ⑦ Corrosion specimens, 3/4", O.D. reduced 0.030", machined from Sch. 40 galvanized steel or steel pipe
- ⑧ 3/4 x 2" specimen separator, PVC, Sch. 40, O.D. reduced 0.015"

Figure 7. Cross-section of USA-CERL corrosion tester.

¹⁶A. Wachter and R. S. Treseder, "Corrosion Testing Evaluation of Metals for Process Equipment," *Chemical Engineering Progress*, Vol 43, No. 61 (1947), p 315.

deposition or corrosion processes occurring on the walls of piping in distribution systems. Corrosion specimens for this tester may be constructed from any material available in 3/4-in., schedule 40 pipe. Specimens are prepared in accordance with ASTM procedures. Each pipe specimen exposes 10.25 sq in. of pipe wall to the water.

Four standard metal coupons can be installed in the test loop, all oriented in the same direction in relation to the flow of water through the loop. The 1/2 in. by 3 in. by 1/16 in. coupons are mounted on a PVC pipe plug by means of a nylon stem (attached to the plug) which protrudes into the middle of the pipe. Each coupon exposes 3.38 sq in. of surface area to the bulk water. The coupons and mounting hardware are commercially available in a variety of materials and the coupons can be readily evaluated by most laboratories according to ASTM procedures.

All of the components of the test loop are assembled with pipe hanger supports on a 4 ft by 4 ft plywood sheet. The completed assembly requires minimal wall space when installed and is easily transported as a complete unit. Ten identical units were assembled for installation at Fort Monroe (five) and Fort Bragg (five).

Possible Experimental Designs

Because of the pipe loop system's segmented, multisample, standardized design, a great variety of experimental designs are possible. Care must be taken so that data can be compared meaningfully and so that the many complicating factors are controlled as much as possible. The system's design is especially useful for side-by-side comparison tests. For example, pipe loops could be used to:

- Evaluate effect on materials of water that has not been treated with corrosion inhibiting chemicals
- Evaluate the effect of water that has been treated with the corrosion inhibiting chemical normally used by the plant in question
- Using multiple loops, compare (side-by-side, simultaneously) the effects of several corrosion inhibitors
- Compare the effects of varying dosages of one inhibitor
- Evaluate the effect of changing the inhibitor used
- Evaluate the effect of changing other aspects of the treatment process (filtration, chlorination, etc.)
- Investigate changes in water corrosivity characteristics over time
- Investigate the variability in the weight loss method of measuring corrosion rates (significant differences in weight loss can occur when active corrosion sites develop on one specimen more easily than on another specimen)
- Determine when the corrosion rate stabilizes, under various conditions.

The design also permits variations in exposure time. For example, four coupons could be placed in a loop at one time, and then removed at staggered intervals: one coupon could be removed after 3 months, one after 6 months, etc.; the last would be

exposed for a whole year. New ones could replace the ones removed so the loop would remain in continuous use. This data could be manipulated in numerous ways. Two factors must be considered in the choice of intervals: seasonal variation and nonlinear change in the corrosion rate. The seasons affect the corrosion rate, partly because of changing temperatures. Second, the corrosion rate of a newly prepared specimen decreases exponentially (roughly) over time. In the more aggressive waters, galvanized steel specimens have been shown to require 12 to 18 months of exposure to approach a minimum stable corrosion rate.¹⁷ A less aggressive water and another material may reach a stable value in much less time. A 1-year interval would include all the seasonal changes and allow the corrosion rate to stabilize. However, the optimum interval has not been determined with certainty.

¹⁷C. Neff, M. Schock, and J. Marden, "Relationship Between Water Quality and Corrosion of Plumbing Materials in Buildings, Volume I: Galvanized Steel and Copper Plumbing," State Water Survey Contract Report 416-I (University of Illinois, 1987).

6 EVALUATING THE PIPE LOOP SYSTEM AT FORT MONROE, VA AND FORT BRAGG, NC

Background on Fort Monroe Water Plant

Fort Monroe receives its potable water supply from its own Big Bethel Water Treatment Plant, Hampton, VA. The water plant also supplies water to Langley Air Force Base and NASA. The plant maintains two reservoirs, with raw water being drawn off the lower reservoir. The water treatment process consists of prechlorination, alum flocculation, settling, sand filtration, fluoridation, and postchlorination. Corrosion control is achieved by adjusting the pH by adding lime; zinc metaphosphate (Virginia Chemical Co. [Virchem] No. 937) is used as a corrosion inhibitor. The finished water is maintained at a pH of 7.3 to 7.5, and phosphate is maintained at 2.5 mg/L as PO_4 . Chemical testing is performed daily at the plant on the treated water in the plant and at several points in the distribution system.

In 1968-69, the Big Bethel Treatment Plant changed the chemical treatment for corrosion inhibition from sodium silicate at a pH of 8.5 to Calgon TG10 (sodium hexametaphosphate). Calgon advised the plant that by feeding TG10, a lower pH could be used to remove iron and manganese. With this treatment scheme no red water problems occurred. For economic reasons, the plant switched to Virchem corrosion inhibitor 937 (zinc metaphosphate). A corrosion coupon study conducted by Virginia Chemical Co. showed corrosion rates of 6.80 to 7.85 mils/year with this treatment. Another coupon testing in December 1982 showed that Virchem 931 (orthophosphate) decreased corrosion rates to 2.81 to 3.79 mils/year. However, red and black water problems appeared when Virchem 931 was used; hence the plant went back to using Virchem 937.

A water quality survey conducted by the Facilities Engineering Support Agency ¹⁸ in July 1983, using chemical analyses and Langelier Index calculations, concluded that the water was extremely corrosive and non-scale-forming at ambient temperatures.

Approximately 42 mi of supply and distribution mains provide potable water to Fort Monroe. These mains have cast-iron piping with leaded bell and spigot type joints. The service lines are galvanized steel and copper. None of the supply or distribution lines at the installation have cathodic protection or cement linings. All of the on-post distribution mains, except 4 in. lines, were "pigged" in 1983, but the lines were not lined with cement after the pigging. Fort Monroe is currently experiencing red water problems with the water supply due to the pigging of lines without subsequent cement lining. However, efforts are underway to replace the old distribution mains.

Background on Fort Bragg Water Plant

Fort Bragg's drinking water source is a reservoir which collects water from the on-post watershed. The water treatment process consists of powdered activated carbon, alum coagulation, settling, sand-anthracite dual-media filtration, fluoridation, and chlorination. Treated water pH is adjusted by adding lime. For corrosion control, Dabco 22 (bimetallic polyphosphate) corrosion inhibitor is added at the end of the treatment process. (However, until January 1987, Virchem 937 was used, as at Fort Monroe.)

¹⁸Water Treatment Survey Report - Fort Monroe, VA" (Facilities Engineering Support Agency, 1984).

Routine finished water analysis is conducted daily at the well-equipped water plant laboratory.

A recent survey of domestic-water-side corrosion found that the water should be corrosive to steel and galvanized steel because it has an unusually low alkalinity (5 mg/l) and is nearly saturated with dissolved oxygen (8 mg/l).¹⁹ The water has no tendency to deposit any protective calcium carbonate scale based on the Langelier saturation index (LSI = -2.3).

The principal corrosion problem associated with conveying domestic water at Fort Bragg involved galvanized-steel pipes and fittings. No significant corrosion problems were associated with copper tubes and fittings. Although no known corrosion-induced leaks were reported in the cast-iron mains, these pipes and fittings were heavily tuberculated. The cast-iron mains (6 to 12 in. in diameter) are being pigged and lined with cement to prevent further corrosion. The water plant personnel reported no current "red water" problems in the distribution system. Such problems had been frequent in the past, before a corrosion inhibitor was used.

Experimental Setup

Equipment

The equipment was identical at both installations: five pipe loops located at various places in the water treatment system. These locations were distributed as shown in Figure 8.

Each loop is operated independently, that is, in parallel with the others. The effluent from loops inside the plant is recycled to the head of the plant, to avoid wasting water. For the loop at the booster station, the effluent flows into a drain. Of the five loops, the control loop, which receives treated water just before any corrosion inhibitor is added, is of vital importance because all others will be compared to it.

Samples

This report discusses data for samples of mild steel (C1010), zinc, and galvanized steel (zinc coated). In the future, results will be available for tests on samples of copper, lead, and cast iron.

There is space for eight samples in each loop: four coupons and four pipe inserts. For the data reported here, each loop had two of each type of specimen: two mild steel coupons, two mild steel pipe inserts, two zinc coupons, and two galvanized steel pipe inserts. Thus all the sample slots were filled.

Exposure Times

The exposure time was 3 months for all samples reported. Tests began in July 1986. The data for Fort Bragg is for the period 22 July 1986 to 23 October 1986; for Fort Monroe, the period is 22 January 1987 to 23 April 1987. The staggered removal concept was not used for these samples.

¹⁹J. R. Myers, "Data Summary Related to the Relative Corrosivity of Soils and Domestic Water at Fort Bragg, NC" (Prepared for USA-CERL by JRM Associates, Franklin, OH, 1986).

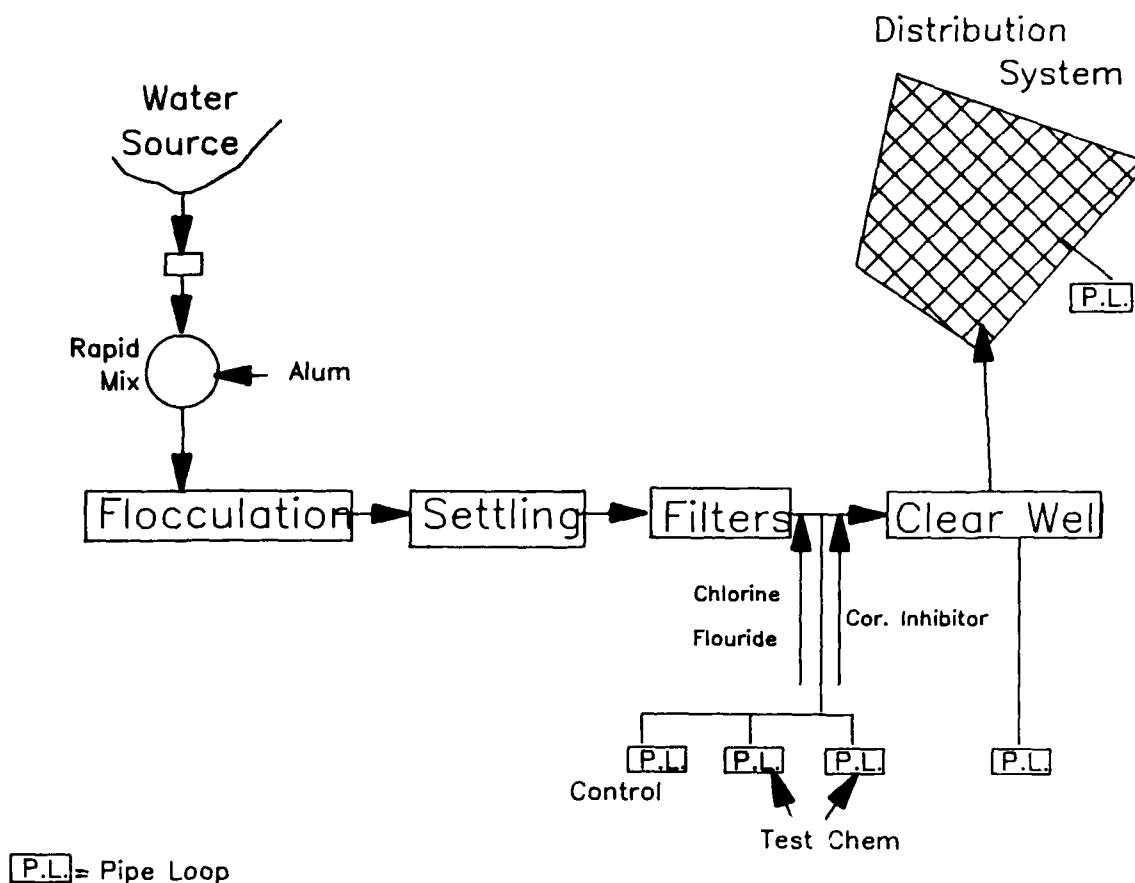


Figure 8. Pipe loop system locations.

Chemicals

At Fort Monroe the general water supply was treated with the corrosion inhibitor Virchem 937, zinc metaphosphate. This chemical reached two loops, the one receiving "finished" water and the loop at the booster pumping station. At Fort Bragg the general corrosion inhibition treatment was Virchem 937 until January 87; after Jan 87 the plant switched to Dabco 22 (bimetallic phosphate). (This change does not affect comparison of the data presented here because during the interval reported for Fort Bragg [July to October 1986] they were still using Virchem 937.)

At Fort Monroe two "extra" chemicals were pumped through the "test" loops, which received fully treated water just before the corrosion inhibitor was to be added. The two chemicals were Nalco 937 and Nalco 7393. The rate at which these test corrosion inhibitors were injected was adjusted so the concentration of inhibitor was maintained at about 1 ppm (1 mg/l). During the interval reported, no "extra" corrosion inhibitors were tested at Fort Bragg. All of the same equipment is in place, however. So, the only comparisons shown for Fort Bragg are among "no inhibitor," "finished," and "distribution system" water.

Typical water quality data from Forts Bragg and Monroe are shown in Table 6.

Table 6
Typical Water Quality at Fort Bragg, NC and Fort Monroe, VA

Parameter	Units	Fort Bragg Water Plant	Fort Monroe Water Plant
pH	pH units	7.4	7.7
CO ₂ , dissolved	mg/L	<5	
O ₂ , dissolved	mg/L	8	
Total alkalinity	mg/L CaCO ₃	5	40
Total dissolved solids	mg/L	77	182
Total hardness	mg/L CaCO ₃	36	126
Calcium	mg/L as Ca	12	
Magnesium	mg/L as Mg	0.78	
Zinc	mg/L as Zn	0.07	0.332
Iron	mg/L as Fe	0.09	0.04
Copper	mg/L as Cu	<0.01	
Manganese	mg/L as Mn	0.03	0.025
Sodium	mg/L as Na	2.2	8.3
Silica	mg/L as SiO ₂	8	
Chloride	mg/L as Cl	14	16
Sulfide	mg/L	0	
Sulfate	mg/L as SO ₄	13	144

Measurement

After 3 months, the samples were removed and taken to the laboratory for analysis. The composition of the deposits was analyzed using x-ray diffraction. The corrosion rate was determined using the ASTM weight loss method (ASTM Standard D-2688-83). In the overall procedure, the samples are:

- Precleaned (ASTM)
- Weighed
- Exposed
- Removed and weighed (to determine weight gained in corrosion byproducts)
- Loose scale removed (ASTM)
- Thoroughly cleaned (ASTM)
- Weighed (to determine material lost overall).

Precautions for Controlling Variability

The following measures were taken to eliminate as much variability as possible and to simulate as closely as possible the actual conditions found outside a treatment plant, in the distribution system.

- Each loop was identical.
- Specimens were put in the same place in each loop.
- A constant water flow of about 3 gpm or about 2 ft/s was maintained (water meters were monitored daily and the flow rate was adjusted as appropriate).
- This constant flow insured that all loops experienced the same ambient water temperature.
- The water quality did change, but all loops in the system experienced the same changes. (As part of normal treatment procedures, the water is routinely sampled to monitor its chemical composition.)

Preliminary Results

The first set of samples was removed from the pipe loop systems for observation and analysis after 3 months of operation. Virtually no maintenance was required, except for occasional flow meter check, during the experimental period. The water meters recorded flows between 2.5 to 3 gpm (corresponding to a water velocity of 1.8 to 2.2 ft/s). The water quality parameters during the experimental period were analyzed and recorded by the water plant laboratory as a part of routine water plant operations.

At Fort Bragg, a visual observation of the flow meter in the pipe loop systems showed that the pipe loop receiving finished water with the corrosion inhibitor was not stained. In contrast, the flow meters of the pipe loop systems which received water just before the addition of corrosion inhibitor were stained dark brown, apparently by the corrosion byproducts. This indicated that the corrosion inhibitor was able to react with and remove the corrosion byproducts which can cause "red water" complaints.

The specimens from the pipe loop systems at Fort Bragg were removed for visual comparison. Figure 9 shows the condition of the interior surface of the mild steel before and after exposure in the pipe loop system which received finished water with corrosion inhibitor. As shown, a layer of deposits accumulated on the interior surface of the pipe. These deposits can be corrosion byproducts or precipitates from the water. Similar effects were observed (Figures 10 and 11) in the galvanized pipe specimen as well as on the mild steel and zinc coupon specimens. The deposits on steel specimens were visually different from deposits on zinc and galvanized specimens. Similar visual inspections indicated very little deposition in any of the pipe or coupon specimens in the pipe loop system which received treated water just before addition of corrosion inhibitor. Perhaps in this system the corrosion byproducts were released into the water, staining the flow meters rather than the coupons or pipes. Hence, from this visual observation, it appears that the presence of corrosion inhibitor in the water had a definite effect on the interaction with the metal specimens in the pipe loop system.

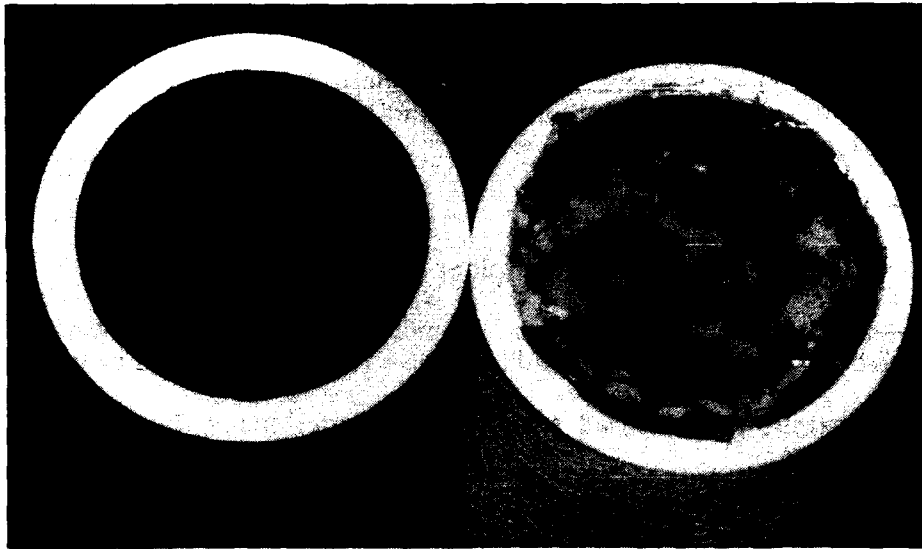


Figure 9. New pipe specimen and pipe specimen exposed to water in pipe loop system.

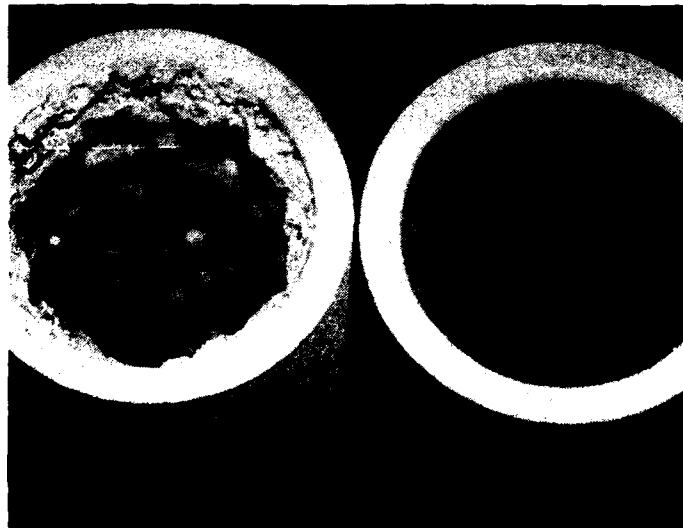


Figure 10. Corrosion byproducts on a galvanized iron pipe specimen exposed to water in pipe loop system.

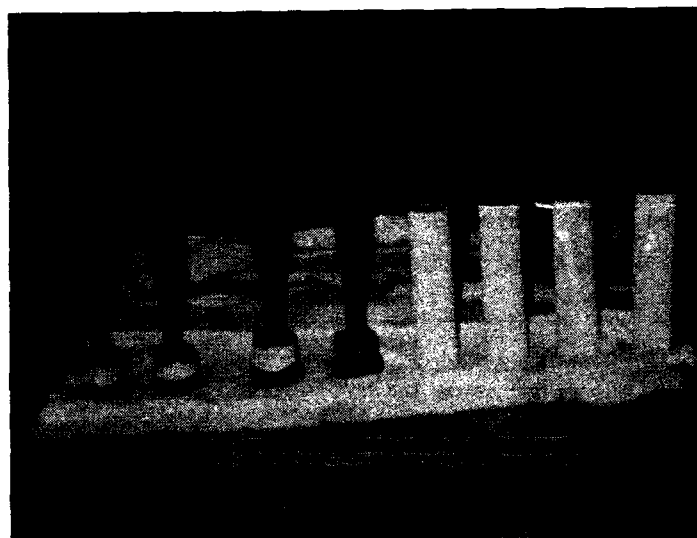


Figure 11. Corrosion byproducts on mild steel and zinc coupons exposed to water in pipe loop system. (From left, coupons are [1] mild steel, [2] zinc, [3] mild steel, and [4] zinc.)

At Fort Monroe, the flow meters in all pipe loop systems were uniformly stained dark brown, indicating that the corrosion inhibitor had no effect which could be visually observed. A visual comparison of the pipe loop system specimens indicated thick deposits on the mild steel specimen surface and a very thin layer of deposits on the zinc and galvanized steel surfaces. Similar deposits were seen regardless of whether the specimen received water with or without corrosion inhibitor.

Further analyses were conducted in the laboratory to characterize the deposits and determine the corrosion rates of the specimens from both installations. Table 7 presents the corrosion rate data for all the specimens removed from Forts Bragg and Monroe during the first three months of operation. In general, corrosion rates of pipe specimens were different from those of coupon specimens of the same material. This may have been because the different shapes of the specimens affected water flow characteristics. Also coupon specimens may have accumulated stresses in their edges during preparation, which may have led to preferential corrosion of the edges. This preferential corrosion of the coupon edges was evident visually after the surface deposits were removed.

Figures 12 and 13 compare the corrosion rates of the specimens in Fort Bragg water without corrosion inhibitor treatment, in the finished water at the plant, and in the distribution system. In general corrosion rates of galvanized (zinc) specimens were lower compared to mild steel specimens. However, as seen in the figures, the corrosion rates of both mild steel and galvanized (zinc) steel were higher in the water which was treated with the corrosion inhibitor. Although an increase in corrosion rate in presence of a corrosion inhibitor was unexpected, it is not an unusual occurrence. Several cases have been reported in the literature where, under certain conditions, the corrosion inhibitors actually increased the corrosion rates of metals. However, this observation could not be confirmed without side-by-side comparison and monitoring.

Table 7

**Preliminary Results of Pipe Loop Experiments at
Fort Bragg and Fort Monroe
(Data for 22 July 1986 to 23 October 1986)**

Location	Water Source	Average Corrosion Rate (mils/year)			
		Steel Pipe	Steel Coupon	Galv. Pipe	Zinc Coupon
Fort Bragg	Water w/o Corrosion Inhib.	5.87	3.16	3.25	1.22
Fort Bragg	Finished Water (Virchem 937)	17.82	12.74	4.70	3.14
Fort Bragg	Distribution System Water (Virchem 937)	16.77	13.23	4.54	2.97
Fort Monroe	Water w/o Corrosion Inhib.	29.19	12.79	7.10	7.42
Fort Monroe	Finished Water (Virchem 937)	21.87	12.38	5.05	5.82

Note: Both Forts Bragg and Monroe treated their water with Virchem 937 as corrosion inhibitor.

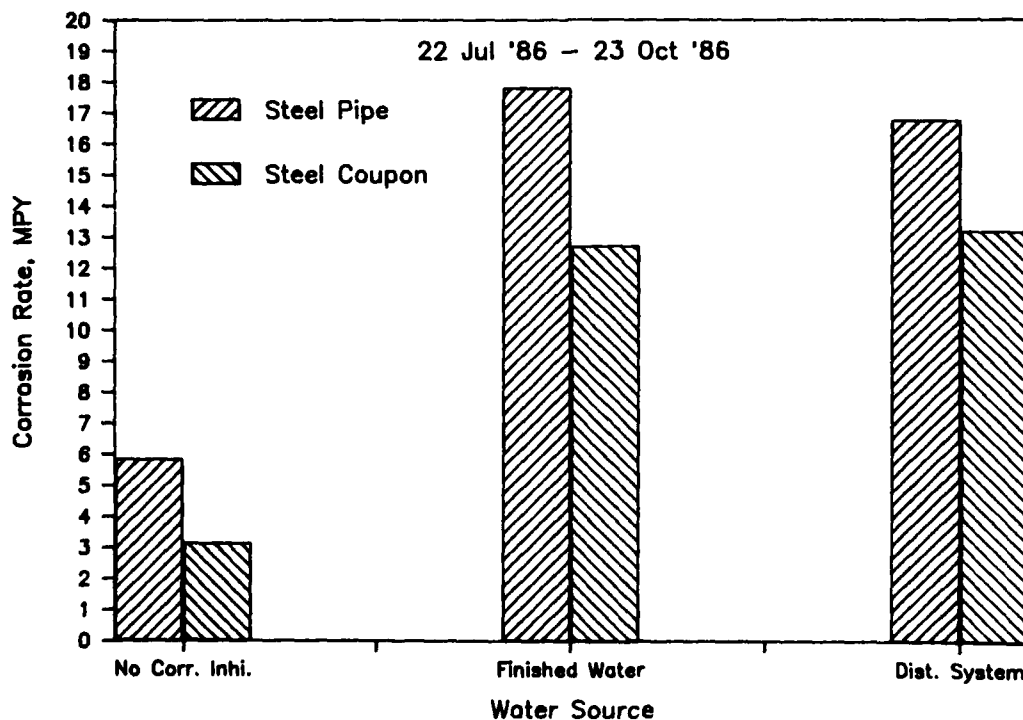


Figure 12. Corrosion rates of mild steel specimens at Fort Bragg, NC.

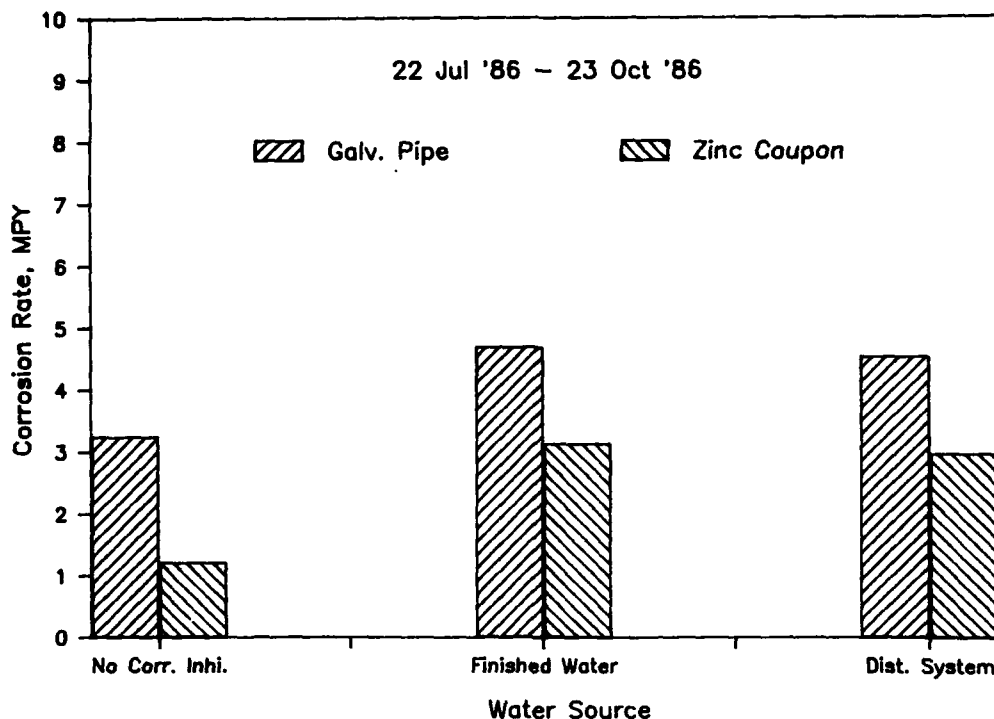


Figure 13. Corrosion rates of galvanized (zinc) iron specimens at Fort Bragg, NC.

Table 8 presents the type and extent of pitting of specimens during the same experimental period as above. It is clear from the table that pitting was the predominant type of corrosion in mild steel specimens, whereas the galvanized specimens experienced a general (uniform) type of corrosion.

Figures 14 and 15 compare the corrosion rates of mild steel and galvanized (zinc) steel specimens in presence of various corrosion inhibitors at Fort Monroe. This data was collected during the period of January through April 1987. The Nalco corrosion inhibitors were injected into the pipe loop system using a pump, whereas the water plant added the Virchem corrosion inhibitor in their finished water supply. As seen from the figures, there were no significant differences in corrosion rates of pipe specimens with or without corrosion inhibitor. However, the coupon specimens did show some reduction in corrosion rates due to the presence of a corrosion inhibitor. Because of the limited experimental time, the data did not show any conclusive evidence regarding the effectiveness of the corrosion inhibitor.

At both Fort Monroe and Fort Bragg, it was clearly evident that the corrosion rates of the specimens during the July to October 1986 period were significantly higher than the corrosion rates during the January to April, 1987 period. This seasonal change in corrosion rates is due to the changes in influent water quality parameters, especially temperature, which plays an important role in the corrosion phenomenon.

These preliminary results are short term (3 months) and hence may not truly reflect the corrosion status. Subsequent long-term studies with the pipe loop system have revealed that the corrosion inhibitors do eventually reduce the corrosion rates of mild

Table 8
Type and Extent of Pitting in Pipe Loop System Specimens

Location	Water Source	Metal	Type of Corrosion	Surface Area Affected	Max. Depth (in.)	Range of Depth (in.)	Width (in.)	Comments
Ft. Bragg	Treated Water w/o Corrosion Inhibitor	Mild Steel	Pitting	30-40 %	0.001	<0.001	0.001	Numerous very small pits, fine streaks on surface
		Galv. Steel	General	<10 %	---	none	---	No penetration of Zn
Ft. Bragg	Finished Water at Water Plant	Mild Steel	Pitting	60-70 %	0.007	0.002-0.006	<0.003	Numerous pits
		Galv. Steel	General	<10 %	---	none	---	No penetration of Zn, grain of metal visible
Ft. Bragg	Finished Water in Distrib. System	Mild Steel	Pitting	70-80 %	0.015	0.010-0.015	0.010-0.025	Numerous pits
		Galv. Steel	General	20 %	--	none	<0.002	
Ft. Monroe	Treated Water w/o Corrosion Inhibitor	Mild Steel	Pitting	90+ %	0.016	0.000-0.015	0.05-0.13	Several large areas attacked, many large pits
		Galv. Steel	General	90+ %	---	none	<0.002	No surface gloss, no penetration of zinc
Ft. Monroe	Finished Water at Water Plant	Mild Steel	Pitting	80-90 %	0.015	0.002-0.008	0.002-0.010	Numerous pits, flow effects
		Galv. Steel	General	30-40 %	---	none	<0.002	Uneven surface, no penetration of zinc

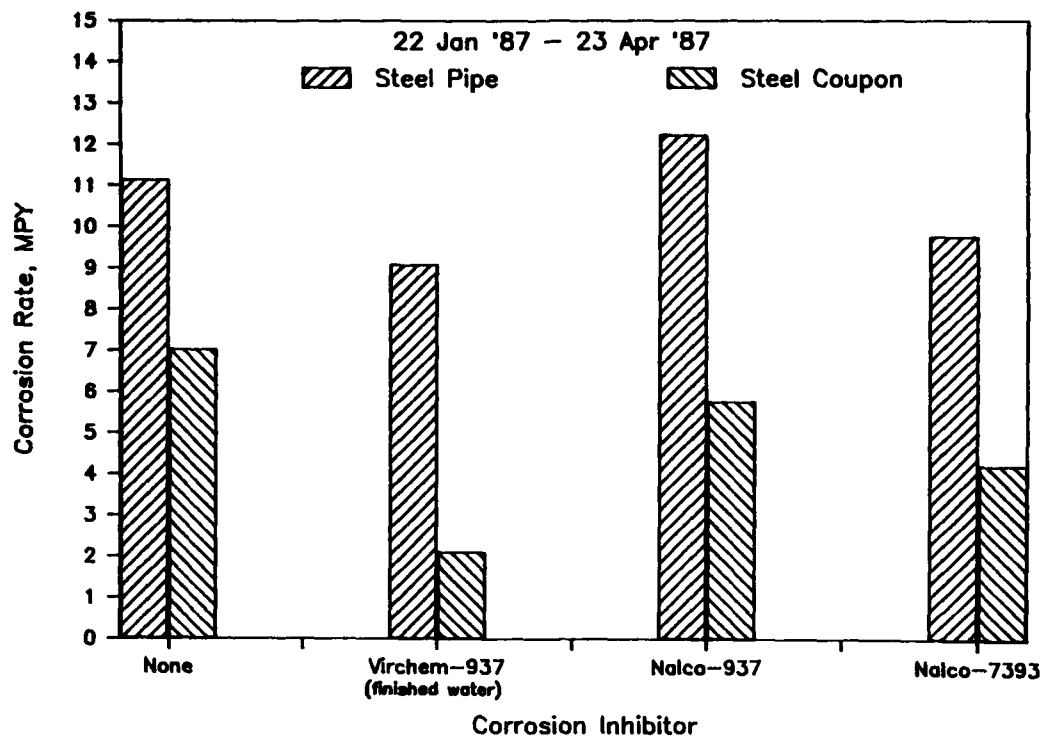


Figure 14. Effect of various corrosion inhibitors on mild steel corrosion rates at Fort Monroe, VA.

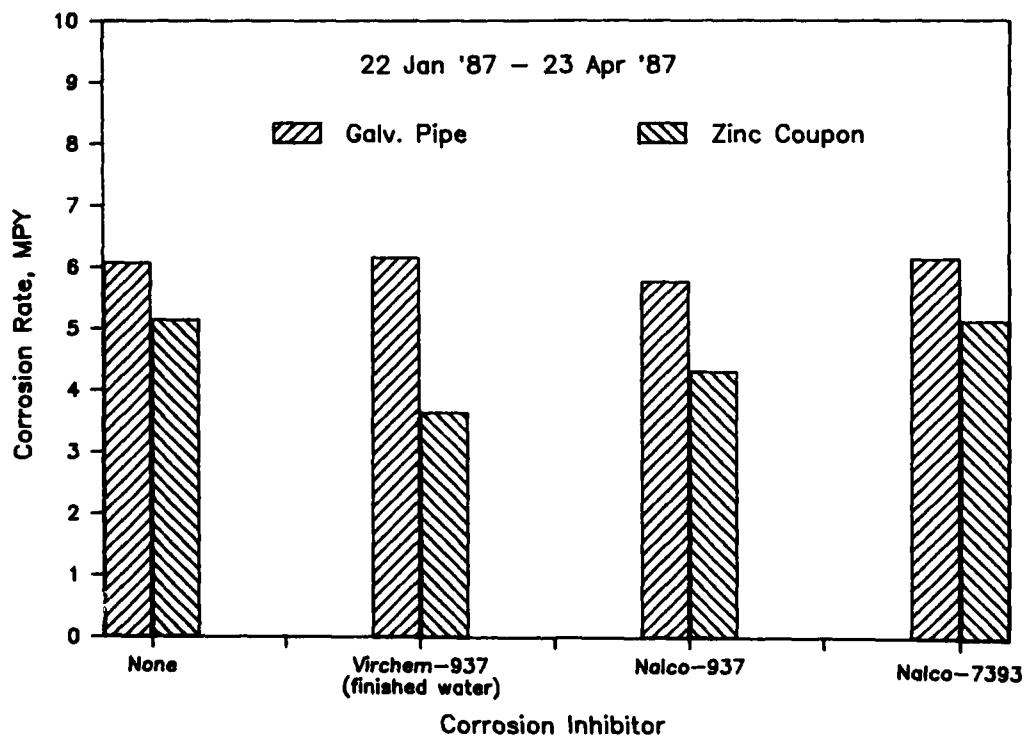


Figure 15. Effect of various corrosion inhibitors on galvanized (zinc) iron corrosion rates at Fort Monroe, VA.

steel. This reduced rate was due to the formation of a thick layer of corrosion products mixed with the corrosion inhibitor, which completely covered the pipe surface. The corrosion rates of the pipes in the loop that received water prior to addition of corrosion inhibitor continued to be high, since no protective coating formed on the pipe surface. The results of this study will be reported in full in a future technical report.

The observations and practical experiences reported in the literature illustrate how difficult it is to fully understand the different effects of corrosion on a complete system. This difficulty arises due to different materials, different water qualities, and incomplete knowledge of corrosion phenomena. The pipe loop system concept is one way of addressing these issues. The preliminary results of its field evaluation have clearly demonstrated, both visually and by corrosion rate determinations, the effect of corrosion control chemicals used in water treatment plants on pipe materials. However, much needs to be done on inhibitor mechanisms, monitoring methods, and cost-effectiveness of analysis.

7 CORROSION CONTROL REGULATIONS AND ECONOMICS

Corrosion Control Regulations

The Safe Drinking Water Act (SDWA) of 1974 (Public Law 93-523) was passed by Congress to ensure that public drinking water supplies are safe for consumption. As a result, the USEPA established the National Interim Primary Drinking Water Regulations (NIPDWR)²⁰ which define maximum allowable concentrations for various contaminants (maximum contaminant levels [MCL]) in drinking water. These regulations will be reviewed at least once every 3 years and can be amended at any time.

One target of these regulations is concentrations of specific trace metals. The USEPA has recognized that corrosion products in a water supply can pose serious health threats to the public. Since corrosion byproducts are the principal source of lead, zinc, copper, and iron concentrations in drinking water, the importance of monitoring the corrosivity of water has increased. The USEPA established secondary drinking water regulations which specifically outline monitoring for corrosion-related parameters.²¹

These secondary regulations state that potable waters should be "noncorrosive," a term that has yet to be defined by any regulatory agency, making compliance with this regulation impossible. Further complications in the regulation of corrosion in the water treatment industry stem from the lack of generally accepted corrosivity measures and the lack of corrosion control methods that are effective throughout the distribution system. Complicating the regulation of corrosion still further is the requirement that corrosion be regulated at "the free flowing outlet of the ultimate consumer of a public water system," which requires a water utility to know about the plumbing materials used not only in the distribution mains but also in the individual consumer dwellings, so it can supply a water that is noncorrosive in both.

Costs of Corrosion Control

It has been estimated that the cost of corrosion to the water works industry is between \$700 million to \$1 billion dollars per year. Although corrosion control cannot completely eliminate the cost of corrosion damages to water distribution systems, substantial savings are possible by implementing some sort of corrosion control program.²²

Tables 9 and 10 give some typical dollar values for various chemicals used in control of corrosion in drinking water systems. It should be stressed that these figures are only representative values for comparison purposes and that actual values will depend on many factors. The cost of installation of corrosion control systems is minimal compared to the cost of repairing and replacing the plumbing damaged by corrosion. Installation costs range from \$5,000 to \$40,000 depending on the size of the system and the type of system (liquid or solid feed).²³ Capital costs are also small when compared to the cost of corrosion damages.

²⁰USEPA, "National Interim Primary Drinking Water Regulations."

²¹USEPA, "National Secondary Drinking Water Regulations," *Federal Register*, Vol 44, No. 140 (1979), p 42195.

²²Singley, et al.

²³*Internal Corrosion of Water Distribution Systems.*

Table 9
Comparative Costs of Corrosion Inhibitors (1984)*

Type	Dosage Rate (mg/L)	Inhibitor Cost (\$/pound)	Treatment Cost (\$/mil gal)
Lime	10-30	0.30	2.50 - 7.50
Caustic Soda	10-30	0.12	10.00 - 15.00
Soda Ash	10-30	0.20	16.70 - 50.00
Sodium Hexameta- phosphate	1-4	0.90	7.50 - 30.00
Bimetallic Phos- phate	0.5-2	1.50	6.25 - 25.00
Zinc Orthophos- phate	0.12-0.5(Zn)	2.25(Zn)	3.75 - 9.37
Sodium Silicate	4-10	0.65	22.00 - 58.00

*Reprinted from *Internal Corrosion of Water Distribution Systems*, by permission. Copyright © 1985, American Water Works Association.

Table 10
Typical Annual Chemical Costs for Corrosion Control (1982)*

Costs do not include freight					
Chemical	Use	Feed rate	Cost per unit (\$)	Cost per year	
				3-MGD plant (\$)	50-MGD plant (\$)
Quicklime, CaO	pH adjustment	1-20 mg/L 8-170 lb/MG	63/ton bulk	277-5,865	4,500-97,700
Hydrated lime, Ca(OH) ₂	pH adjustment	1-20 mg/L	78/ton bag	342-7,254	5,700-121,000
		8-170 lb/MG	65/ton bulk	285-6,045	4,750-101,000
Caustic soda, NaOH (50% solution)	pH adjustment	1-20 mg/L 12-150 lb/MG	200/ton bulk	1,310-21,900	27,400-456,000
Soda ash, Na ₂ CO ₃	pH adjustment	1-40 mg/L	16/cwt bag	1,402-61,320	23,400->1,000,000
		8-350 lb/MG	152/ton bulk	666-30,375	11,100-506,000
Inorganic phosphates	Inhibitor	3 mg/L 25 lb/MG	65/cwt bag	17,800	297,000
Sodium silicate	Inhibitor	2-8 mg/L 17-67 lb/MG	5.00/cwt tank	930-3,670	15,500-61,200

*Source: J. E. Singley, et al., *Corrosion Prevention and Control in Water Treatment and Supply Systems*, Pollution Technology Review No. 122 (Noyes Publications, Park Ridge, NJ, 1985), p 89. Information originally obtained from various chemical suppliers. Used with permission.

The estimated cost of a lime, soda ash, and sodium silicate storage and feeding system for Seattle's 200-mgd Cedar supply in 1980 was \$900,000.²⁴ Table 11 gives some figures for the Seattle Water Department's corrosion control program, which show that the main cost in such systems is the chemicals. The use of corrosion inhibitors can reduce the cost of corrosion damage by 15 to 50 percent, corresponding to a reduction of \$150 million to \$500 million annually.²⁵ The great variability in these figures suggests that savings are possible; however, general projections of actual savings are not possible and economic analyses must be done on a case by case basis.

Table 11

Total Costs of Corrosion Control Treatment (1979)

Cost Item	Cedar River \$/mil gal	Tolt River \$/mil gal	Total \$/mil gal	Percentage of Total
Capital Facilities	1.55	3.10	2.07	22.3
Chemical Cost	2.71	13.12	6.18	66.5
Labor	0.33	0.66	0.44	4.7
Maintenance	0.16	0.32	0.22	2.4
Power	0.04	0.08	0.06	0.6
Additional Chlorine	0.33	0.33	0.33	3.5
TOTAL	\$5.12	\$17.61	\$9.30	100.

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²⁴Internal Corrosion of Water Distribution Systems.

²⁵Internal Corrosion of Water Distribution Systems.

8 CONCLUSIONS AND RECOMMENDATIONS

USA-CERL designed and developed an apparatus known as the "pipe loop system" (Chapters 5 and 6) to objectively evaluate the effectiveness of water quality control chemicals for protecting the water infrastructure. The pipe loop system consists of common, commercially available components, installed compactly on a 4 ft by 4 ft plywood sheet. Using it, several metal coupons and lengths of pipe can be exposed to water at a particular stage in the treatment process. The system's standard, multispecimen design lends itself to a multitude of experimental designs, but it is especially suited for side-by-side, simultaneous testing. Corrosion rates are measured using the weight loss methods specified in ASTM Standard D-2688-83.

The pipe loop system was installed and tested at Fort Bragg, NC, and Fort Monroe, VA. It was used at these sites to perform side-by-side comparisons for evaluating water quality control chemicals. Preliminary results are reported here only to illustrate the use of data from this system:

- Corrosion rates. At both installations, pipe inserts corroded faster than coupons which were exposed to the same water. At Fort Monroe, the coupons corroded less in the water treated with corrosion inhibitor, but no difference could be determined for the pipes. At Fort Bragg, the corrosion rate appeared to be greater for specimens in treated water.
- Type of corrosion. Mild steel specimens exhibited significant pitting. The corrosion of the galvanized steel specimens was more general.
- "Red water" problems. At Fort Bragg the normal corrosion inhibiting treatment seemed to prevent "red water," while at Fort Monroe it did not.

The data presented in this report should not be taken as a comprehensive evaluation of the treatment chemicals used. Further study is needed to demonstrate the full capability of the pipe loop system and to establish standard operating procedures (SOP) for specific uses.

METRIC CONVERSION FACTORS

1 mil	=	0.001 in.	=	0.00254 cm
1 in.	=	2.54 cm		
1 sq in.	=	6.45 cm ²		
1 ft	=	0.3048 m		
1 sq ft	=	0.093 m ²		
1 gal	=	3.785 l		
1 oz	=	2835 mg		
°F	=	(°C x 1.8) + 32		

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